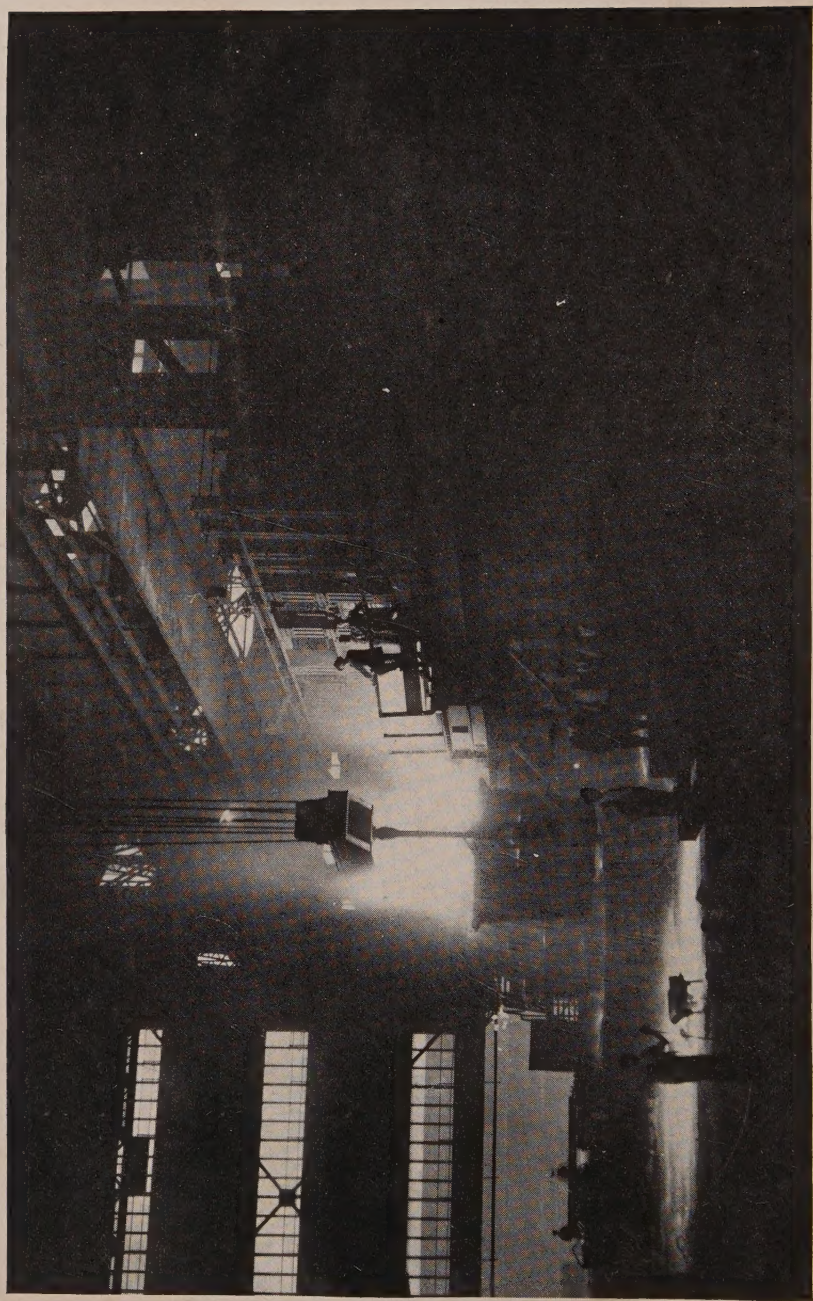


Pittsburgh Forgings Company

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Frontispiece—An Alloy Steel Cast in a Sheffield Acid Open-Hearth Works.

The Application of Science to the Steel Industry

By

DR. W. H. HATFIELD

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of the American Society for Steel Treating.

DR. W. H. HATFIELD

EDWARD DE MILLE CAMPBELL MEMORIAL LECTURER—1928

DR. W. H. HATFIELD was born in 1882. His scientific and metallurgical education was received at Sheffield University, where he graduated and was both Mappin Medalist and Carnegie Scholar.

He is a member of the Council of the Iron and Steel Institute (Chairman of the Steel Ingots Committee, as well as that of the newly formed

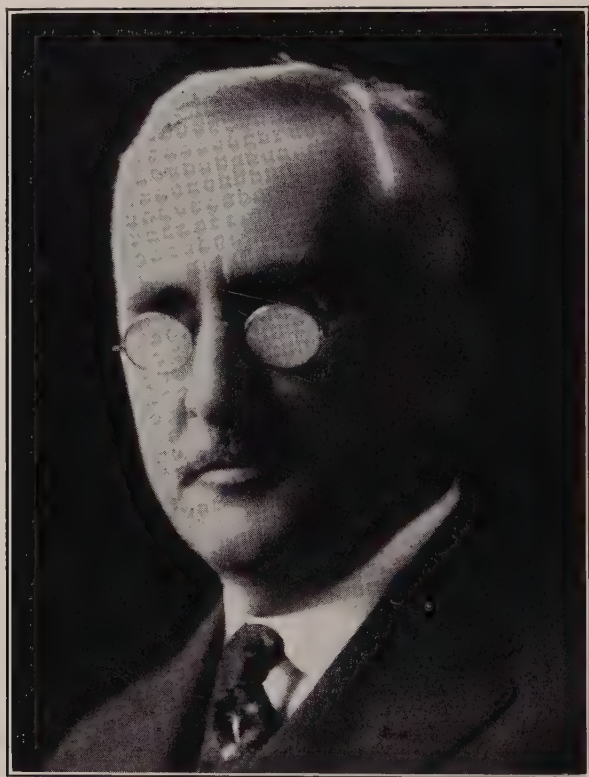


DR. W. H. HATFIELD

Corrosion Committee), a member of the Institution of Mechanical Engineers, Automobile Engineers, Royal Aeronautical Society, Faraday Society. Past President of the Sheffield Metallurgical Association and a member of numerous other British technical committees and societies.

For many years Dr. Hatfield has been associated with the Brown-Firth Research Laboratories, which, it is well known, contributes to the scientific

and technical progress of one of the largest European interests—one of the firms, Messrs. John Brown and Company, was responsible for the building of a large portion of the Grand Fleet, and the other associated firm, Messrs. Thos. Firth and Sons, Ltd., having produced huge quantities of shells during the war. Since the signing of the armistice, the research work of the laboratories has been along the lines of development of rust and acid resisting steels and the phrase “Firth-Stainless” is well-known. Problems involved in the construction of modern power generating plants



Professor Edward DeMille Campbell
1863—1925

have also been in the forefront of their studies, while special steels generally have had much of their attention.

Dr. Hatfield is the author of “Cast Iron in the Light of Recent Research,” which has had wide circulation in the United States as well as in Europe. He has also presented some fifty papers on the various phases of the development of iron and steel and kindred subjects, before numerous European and American technical and scientific societies.

Table of Contents

PAGE

Introduction	1
--------------------	---

SECTION II

Steel Making	10
Crucible Steel	10
Acid Open-Hearth Process.....	11
Electric Steel Making Processes.....	13
Nonmetallic Inclusions and Gases Found in Steel.....	13
Methods of Oxygen Determination.....	17
Gases in Steel	20
Temperature Measurements	22
Ingot Making	29

SECTION III

Manipulation and Treatment	46
Heating for Hot Work	46
Normalizing and Annealing	50
Hardening and Tempering	51
Effects of Forging on Structure and Properties	55
The Thermal Conductivity of Steels. Influence of Composition and Temperature	58
Influence of Composition on Thermal Conductivity of Steels.....	60
Influence of Temperature on the Thermal Conductivity of Steels.....	62
Specific Heat of Steels as Affected by Temperature and Composition...	63
Specific Heat of Pure Iron	64
Effect of Composition	65

SECTION IV

Special Steels	66
Wear Resisting Steels	75
Magnet Steels	77
Permeability of Steels	82
Nonmagnetic Steels	84
Steels of Low Coefficient of Expansion	85
Steels of High Electrical Resistance	86
Causes of Failure	87

SECTION V

Corrosion and Acid Resisting Steels	88
Corrosion Tests	93
Mechanical and Other Properties of the Steels as Affecting Their Appli- cation	100
The Chromium-Nickel Steels (4), (5) and (6).....	102
Concluding Observations	104

SECTION VI

Effect of Temperature Upon Steels (Including a Treatment of Heat Resisting Steels)	106
The Influence of Temperature on the Fatigue Properties of Steel.....	115
Influence of Temperature on the Behavior of Steels Under the Im- pact Test	118
Corrosion at the Higher Steam Temperatures	121
Heat Resisting Steels	122
Scale Resistance of Heat Resisting Steels.....	132

SECTION VII

Tool Steels and Cutlery	139
Carbon Tool Steels	140
High Speed Steels	143
Cutlery	146

THE APPLICATION OF SCIENCE TO THE STEEL INDUSTRY

BY DR. W. H. HATFIELD

INTRODUCTION

TO BE invited by American scientists and technologists to give the 1928 Lecture in memory of Professor Edward de Mille Campbell, is indeed an honor deeply felt by the author. The period which Campbell's work covered was a constructive one of the first magnitude in the development of the metallurgy of iron and steel. The work of the investigators of those years might be compared with trekking into unknown territory. We, today, are largely engaged in following up and intensely studying the ground they first turned over; in some cases using the same methods, in others, having the advantage of new instruments and even new lines of attack. Their achievements, however, put ferrous metallurgy upon its feet. In that period, the imagination and the constructive mental ability of Professor Campbell came into play, and his effect upon contemporary work was due not only to his contributions to knowledge, but also to the impetus given to the experimental work of others by the theoretical views which he invariably put forward concerning the work upon which he had been engaged. The matter and manner of his writings always engaged the most serious attention upon our side of the Atlantic.

The versatility of his genius is displayed in the titles of his contributions covering the period 1885 to 1926; his indomitable pluck, by the fact that from the age of 28 his work was continued under the disability of blindness resulting from his tragic accident while investigating the constitution of steel.

His early work, and it was invaluable, contributed to placing the analysis of steel upon a practical basis. His work upon the constitution of steel, with particular reference to the condition in which the carbon occurred, extended over a long period, and was interspersed with efforts in several directions, notably on the diffusion of sulphur, the heat of formation of carbides and silicides, dry air blast as applied to blast furnaces; whilst his later

period was given up to such diverse problems as the effect of hydrogen, the hardness of steel, the physical properties of steel, the constitution of chromium steel, and he lived to take a great interest in the newest development in our subject, viz., the X-ray method of attack. His field was very large, and his genius invariably illuminated each subject that he touched. He was too earnest an investigator and too daring a theorist to expect all of his deductions to be confirmed as knowledge unfolded itself, but of his niche in the Valhalla of our sciences, there is no doubt.

How can I best speak to you in commemoration of his efforts? After very serious consideration I came to the conclusion that, in view of Professor Campbell's wide field, I was encouraged to make my subject "The Application of Science in the Steel Industry." I do so with less diffidence, since I come from afar, and it may be useful to you to have a view of matters as they exist today—from a European standpoint.

Metallurgical investigation has progressed far, but as one actively engaged in the field of research and in the application of science to the industry, I am overwhelmed when I realize how much there is that we still do not know; when I realize how many of the simplest expedients in the industry are archaic, and how relatively backward is science in supplying the knowledge of natural law necessary for advancement; with many of the commonly accepted and so-called "facts" which I really believe are not facts at all.

The essential functions of scientifically trained men engaged within an industry consist in improving either the processes or the products of that industry by the application of new knowledge available either (a) as the result of independent research, pursued with or without special reference to the industry, or (b) rendered available by a patient research within the industry. The financial resources necessary for the work coming under category (b) are now being reasonably provided in some industries, and with gratifying results in regards to technical progress yielding increased amenities and convenience in one direction or another. With regard to the increasing of knowledge under category (a), the position is hardly as satisfactory, since it involves the effort of many capable investigators over longer periods of time without any immediate prospect of financial return. Indus-

trial enterprise, unless it is very broad minded and is sufficiently prosperous to "cast its bread upon the waters," is inclined to leave the extension of purely scientific knowledge to the enthusiasm of the relatively small band of scientific men whom nature has endowed with the spirit of enquiry, the intellect, and the natural aptitude so requisite for the work. I think that every modern State should study most intensively and then put into effect the best means it can devise for ensuring that such gifted men (and women) as may be born thereto are enabled to work in a suitable environment, and with adequate resources for experiment. It needs them all. This may seem rather a platitude, but the experience of the times clearly indicates that with so much accomplished in the industrial world on the efforts of substantially unassisted fundamental scientific progress, how much more may be accomplished by adequate encouragement and facilities. In America, Britain and elsewhere much is now being done, but not sufficient. No service to the State transcends in value that which can be rendered in increasing our knowledge of the laws and possibilities of nature, and perhaps the time may come when this will be more generally realized. Next in value comes the service of the men who can apply such new knowledge to the good of the State. Indeed, those who can apply such knowledge successfully have, in addition to their adequate understanding of the matter with which they are dealing, frequently to extend still further the knowledge for its complete application. Thus comes the great difficulty of defining what might be considered in the one case, to be the work of the "pure" and, in the other, that of the "applied" scientist. I hope to show that even as regards our own mundane iron and steel industries, no line of demarcation can be drawn.

A man engaged in applying science to industry, has inevitably, on numerous occasions, to deplore his lack of opportunity and time, to follow up the threads of fundamental knowledge with a view to providing information which he considers essential to an adequate solution of his problem, but which is as yet lacking. These extensions of knowledge may be of such an order that their gradual achievement can only be hoped for, as a result of the collective work of the scientific world; on the other hand, the desired information might in certain cases surely be yielded

as a result of immediate careful and patient work in "pure science." Of the former kind, is a more complete knowledge of the nature and the constitution of matter involving the nature of the atom, of cohesion, of "chemical" combination, of the nature of solution (particularly of so-called compounds); of the latter kind, the mastering of problems in physical chemistry, of the determination of physical constants under difficult conditions. Many other problems can, of course, be cited.

The problems engaging attention in the industry are generally those of introducing new, or modifying old processes, or introducing new, or improving old products; generally surmounting difficulties and eliminating defects. A very wide field of science is necessarily laid under contribution, and it surpasses the ability of the individual mind to be expert in each branch of science necessarily called into play in dealing with even any one particular industry. It thus follows that a modern research institution, such as the one the author has the pleasure of directing, is necessarily divided into a number of laboratories, chemical, physical, mechanical, corrosion, metallographic, pyrometric, heat treatment, etc., each section having at its head a man particularly specializing upon his subject. Of the utmost importance is the free exchange of knowledge and ideas between the several sections, since although specialization is necessary, the general bearing of any work undertaken must never be lost to sight.

In surveying the steel industry, one is first struck by the present extravagant use of fuel, or energy, in the metallurgical and reheating processes. Iron and steel are certainly produced "cheaply" from our present point of view, but when one considers the present blast furnace plus refining furnace procedure, in which perforce abnormal fuel consumption is largely caused by the introduction of 3 to 4 per cent of carbon into the metal in the blast furnace and its subsequent elimination in the steel making process; surely it may be concluded that we shall receive a passing smile from posterity. The achievement of efficient direct reduction on a large scale in terms of energy consumed is a foregone conclusion, but its realization involves technical optimism, a long purse and a severe economic struggle. It is a big idea, and in America may be realized. The author has heard rumors of prac-

tical attempts over here of which he hopes to learn more during this visit.

Turning to current processes, the overall efficiency of the coke crucible steel making furnace as still used by some of the Sheffield steelmakers, is as low as 2.5 per cent, the open-hearth does not exceed 17.5 per cent, whilst the efficiency of the electric steel making furnaces is of the order of 10 per cent. This latter value is very low for our latest metallurgical success in this field, but is, of course, due to the present large margin of room for greater efficiency as regards the practical achievements of those responsible for power production. The devices which we now know as power producing units with 15 to 25 per cent efficiency must be necessarily only a passing phase, and it is noticeable that, in his desire for improvement, the electrical engineer is now asking for greater assistance from the metallurgist; calling upon him to modify and to improve the properties of his materials, with a view to securing greater efficiency by the more effective utilization of well-tried laws. The metallurgist welcomes the opportunity to help, and on this matter the author will have something to say later. Nevertheless, great advances will, no doubt, be made by the physicist, who is able to soar above the limitations of the ordinary rut of practice. The author is led to wonder as to the possibilities of entirely new methods for rendering available the required energy for our processes. Electric fuel cells working under reversible conditions and other ideas as yet unborn giving 95 to 100 per cent efficiency¹ may, for the time being, be unrealizable dreams, but we may expect much from the physicist in fundamentally modifying our industrial efficiency in this respect. The efficiency of our reheating and treatment furnaces similarly present a field for immediate practical and far more distant and ultimately successful treatment.

The production of steels of improved mechanical and more useful physical properties, has proceeded apace during the last few decades, and the development in this field is by no means exhausted. The mastering of the details of technique necessary to give increased reliability can be said to have progressed concurrently with the development of the new steels. These aspects were never more thoroughly emphasized than by Lindbergh's flight

¹U. R. Evans, Glasgow Technical College Metallurgical Club Journal, 1926.

from America to Europe, and when at the banquet given to Colonel Lindbergh at the Savoy Hotel in London by our British scientific and technical people, the author listened to the Colonel's description of the trip, how for hundreds of miles in a dense fog he held on in justifiable faith in his machine, it was clear that, metaphorically speaking, hats were taken off not only to his great skill and pluck, but also to contemporary aero engineering and ferrous metallurgy. British metallurgy may reasonably claim its mead of praise in connection with the recent achievement of the Schneider cup.

Can we hope further for fundamental improvements in the properties of metals? Surely the hope is encouraged by isolated indications such as the work of the physicist Griffiths² on quartz. Physical considerations led him to suppose that the intrinsic strength of solids was not achieved in practice owing to extraneous effects. This was demonstrated by experimentally raising the ordinary value of about 25,000 pounds per square inch for a glass, to a value of nearly 500,000 pounds per square inch. By his process of preparation and the elimination of "flaws" this remarkable result was achieved. Is it too much to suppose that steels have intrinsic strengths far above their present determined values and that possibly some means for moving in that direction may be found? We may permit ourselves the fond hope that such is the case.

Industrial metals are crystalline aggregates, and a true knowledge of the nature, not only of the crystal, but also of the aggregate, is of fundamental importance to the investigator. To understand the structure of pure metallic crystals is much easier than to appreciate the manner in which crystals of complex solid solutions are built up. There is much we do not know, but since the original classical work of Carpenter and Elam on the growth and properties of single metallic crystals, our knowledge of the individual crystal has greatly increased, and we are better able to understand the properties of the aggregates. Indeed, one great theoretical advance has resulted from this new work, in that it is not now found necessary to postulate a film of under-cooled liquid metal as existing between the several crystals of the aggregate. Such a hypothetical film constituted a theoretical panacea, since it was

²Mr. Griffiths, *Philosophical Transactions*, 1920, 221A, p. 163.

found too easy to attribute the requisite properties to this film for explaining many problems. Nevertheless, the author would be the first to appreciate the value of Rosenhain's advocacy of this theory from the point of view of its discussion and research-provoking character. Whilst, however, our knowledge is being further increased, and largely by the X-ray method of attack due primarily to the efforts of Sir W. H. Bragg, Hull, Debye and Scheerer and Westgren, we cannot yet be said to understand completely the nature of the crystalline matter of which our metals consist.

To Professor Desch, F. R. S. of the Sheffield University, you were recently indebted for an extremely interesting discussion³ upon the growth of metallic crystals in the light of knowledge extant, and many directions were indicated in which investigations are required.

The eternal problem as to why quenching hardens steel has recently been discussed in a very interesting manner by Jeffries in the last Campbell Memorial Lecture, but can it be said that finality is reached?

Again, take for instance, the effect of cold work. Why is the hardness of a metal increased as a result of cold deformation? Why is this effect, in the case of certain austenitic steels, accompanied by a change of phase? It would be easy to write at considerable length concerning what possibly happens, but to the author it would seem profitless to do so, since our knowledge of the atom, of interatomic forces, and consequently of the nature of cohesion, is not, as yet, sufficiently complete.

The limitation of our ability to understand completely many of the problems occurring as regards ferrous alloys at high temperature, is well illustrated by the state of our knowledge concerning the mechanism of the formation of graphite in pig iron. The author's view⁴ is that the material collecting in the bath at the bottom of the blast furnace consists of an impure saturated solution of carbide in iron. As this cools down to the freezing range, carbide is thrown out of solution, which simultaneously dissociates into iron and carbon, with the production of kish. The iron then freezes, the eutectic splitting up into austenite (solid solution) and carbide, which latter constituent, controlled by the prevailing

³Professor Cecil B. Desch, Lecture before the American Institute of Mining and Metallurgical Engineers, 1927, February.

⁴W. H. Hatfield, "Cast Iron in the Light of Recent Research."

conditions of rate of cooling and composition, either persists or dissociates. Further cooling causes the gradual precipitation of further free carbide, which is governed by considerations similar as regards stability as the carbide separated at the eutectic change point. When we arrive at the temperature at which the pearlite forms we still have the solid solution of eutectoid composition, which now resolves itself into carbide and free iron. The carbide will, again, either dissociate, with the production of perfectly soft pig iron, free from combined carbon, or will persist, and be recognized as the pearlite in the final iron. Satisfying as this is to the author's mind, it apparently by no means meets with general acceptance. R. Ruer⁵ claims that as a result of studying the melting and freezing of white iron, he has obtained evidence of the austenite-graphite eutectic. R. Ruer and F. Goerens⁶ describe the experimental investigation of series of iron-carbon alloys and deduced the direct separation of graphite from solution; they place the graphite eutectic point at 2105 degrees Fahr. (1152 degrees Cent.). K. Tawara and G. Asahara⁷, as the result of an interesting research, arrive at the conclusion that the carbide dissociates in solution and that the carbon is precipitated as graphite. R. Ruer and J. Biren⁸ consider that the carbon is precipitated as graphite and the same view is again expressed by R. Ruer⁹. Further argument on the same line is to be found in the work of H. A. Schwartz and his collaborators¹⁰. On the other hand the view the author favors meets much support. G. Cesaro¹¹ deduces that the carbide is in solution as such. O. Ruff and W. Borman¹² deduce that graphite is only produced by the dissociation of precipitated carbide. K. Honda and T. Murakami¹³, discussing the results of a

⁵R. Ruer, *Zeitschrift für angewandte Chemie*, Vol. XXXI, 1918, pp. 242-244.

⁶R. Ruer and F. Goerens, *Ferrum*, Vol. XIV, 1917, p. 161.

⁷K. Tawara and G. Asahara, *Journal*, College of Engineering, Tokyo, Vol. IX, 1918, p. 127.

⁸R. Ruer and J. Biren, *Zeitschrift für Anorganische und Allgemeine Chemie*, Vol. CXIII, 1920, p. 98.

⁹R. Ruer, *Zeitschrift für Anorganische und Allgemeine Chemie*, Vol. CXVII, 1921, p. 249.

¹⁰H. A. Schwartz, *Transactions*, American Institute of Mining and Metallurgical Engineers, 1922.

¹¹G. Cesaro, *Journal*, Iron and Steel Institute, Vol. 1, 1919, pp. 447-455.

¹²O. Ruff and W. Borman, *Ferrum*, Vol. XII, June, 1915, p. 124.

¹³Kotaro Honda and T. Murakami, *Science Reports of Tohoku Imperial University*, Vol. X, September, 1921, p. 273.

valuable research, conclude that graphite is formed as a result of the catalytic effect of CO or CO₂ upon the precipitated iron carbide. L. Northcott¹⁴ also arrives at the conclusion that the carbide is necessarily precipitated prior to the liberation of the graphite, K. Honda and Hikoze Endo¹⁵ give strong experimental support of this view as a result of measurement of volume changes. It will be seen that the whole matter turns on whether or not the carbide of iron is in solution in the liquid steel as such, or whether and to what extent, the carbide dissociates when in solution. This of course, brings up the whole question as to the mechanism of solution of chemical compounds, but it will be seen that until clarity is achieved as regards ideas in that direction, no dogmatic deduction can be made concerning even so apparently simple a problem as the mechanism of the formation of graphite in pig iron and in iron-carbon alloys generally.

In the foregoing observations it has been the author's desire to reiterate and to emphasize how great indeed is the field awaiting exploration by the investigator, and how essential it is to do all that can possibly be done, to see that the suitable men have adequate encouragement and resources. Physics and chemistry, if indeed one can look upon chemistry as other than a branch of physics, are the basic sciences upon which industries depend for their gradual evolution to a better state of things, and, indeed, at times, for their preservation and even for their creation. These basic sciences and the men responsible for them should be honored and supported. This is one of the author's principal deductions. It has also been said quite truly that the scientific man who wishes to apply science to industry should endeavor to understand the human element in industry; that is rather a difficult requirement, since it involves the necessity that a mind engaged in looking for absolute truth, shall at the same time maintain full appreciation of, if one dare say it, the element of "original sin." Surely it can be claimed as the further deduction that industry generally should learn to know, to appreciate and to make the best use of the scientist.

Time may come, but not before "Homo Sapiens" is on the de-

¹⁴L. Northcott, *Foundry Trade Journal*, June 19, 1924, pp. 515-521.

¹⁵Kotaro Honda and Hikoze Endo, "On the Volume Change During Solidification in Cast Iron and Pure Iron," *TRANSACTIONS, American Society for Steel Treating*, Vol. IX, 1926, p. 967.

eline, when all natural phenomena have been observed and duly docketed. Then, will be an opportunity for one of your wonderful American card index systems, and in the words of Professor E. W. Hobson, F. R. S.¹⁶ "Completely rationalized physics and chemistry would contain within themselves, in the form of postulates, every element which could be supplied by physical observation, and would no longer be dependent for their future progress upon the work of the experimenter. Laboratories would then be useful only for illustrative, didactic, and suggestive purposes, just as drawings and models are still used in geometry, but they would no longer hold their present indispensable position in relation to research."

The author might add that in that golden age, there need be no distinction between pure and applied science or between theory and practice.

SECTION II

STEEL MAKING

Although the manufacturing processes utilized for producing steel from the raw materials cannot be described as being scientifically exact, they are, in each instance, approaching that condition. Whereas until comparatively recently, it was usual to speak of the "art" of steel-making, today it can be stated that the physical chemistry of the processes is being gradually mastered. Whilst some of the reactions are incompletely interpreted, some of the more important are sufficiently well understood. On the other hand, the effect of the reactions upon the constitution of the resultant steels is far from explored, and this is particularly marked as regards the origin and nature of the non-metallic matter found within the structure and also as regards the composition, quantity and effect of the gases remaining in the steel. The author, therefore, feels that he can usefully discuss these matters in the hope of directing increased attention to them. The processes most largely used in the production of the higher grade steels are, the crucible, acid open-hearth and electric processes.

CRUCIBLE STEEL

The crucible process is still in use in Great Britain for the

¹⁶Professor E. W. Hobson, "Science and the Nation," Cambridge University Press, 1917.

production of the special "tool" steels, particularly for the production of high speed steel. The process is very simple. The specially selected pure raw materials are melted in a highly refractory fireclay crucible. The fireclay is rendered stiff enough at the high temperatures by the admixture of a small proportion of coke dust. Thus the charge tends to take up a little carbon from the crucible and also, owing to the permeability of the crucible walls to the furnace gases, a little sulphur is also taken into the steel. Apart from these effects, it can be considered that "what you put into the pot, comes out of it." It is customary to melt the charge and then to retain the crucible in the furnace for the metal to acquire the necessary superheat, during which latter period a slight reaction takes place between the metal and the crucible and slag formed on the upper surface of the metal, which results in an increase of silicon in the steel and, if sufficient manganous oxide is present in the slag, of manganese also. It is usual to add a little manganese to the crucible a short time before teeming. A little aluminum is usually added as the ingot is poured. The great advantage of the process is that while it is expensive, it is still conducted as an "art." The smallness of the crucible and charge enables each ingot to be teemed with care and understanding, thus facilitating the production of the special tool steels free from defects. The smallness of the ingots also reduces the possibility of pronounced heterogeneity through differential freezing, and incidentally prevents the coalescence of non-metallic matter into the larger particles found in heavy ingots. It is of interest to record that the firm founded in Sheffield by Huntsman, the inventor of the process in 1744, and which, being associated with my firms, utilizes our research resources, is still most actively engaged in producing a very superb quality of this steel. Fig. 1 well illustrates the care even now taken in the teeming of the individual crucible ingot.

ACID OPEN-HEARTH PROCESS

In Britain, much of the carbon, nickel, nickel-chromium and nickel-chromium-molybdenum steel is made by the acid open-hearth process which has lent itself admirably for the purpose. Although the flame produced by the combination of the gas and



Fig. 1—Photograph Showing the Teeming of the Individual Crucible Ingots.

air, plays over the hearth, the metal becomes covered at an early period with a slag, the composition of which is controllable between sufficiently narrow limits to permit of a reasonably satisfactory control of the process of refining. The special alloys and additions can be conveniently melted into the charge in the furnace; and large casts can be turned out within very narrow ranges of composition. By synchronizing the production of the steel in two or three furnaces, the largest ingots required can be effectively made. It is essential in this process to use only the low sulphur and phosphorus irons, since these elements are not eliminated, the reactions centering round the elimination of carbon, silicon and manganese by reaction with a slag consisting essentially of ferrous silicate, in which the oxides of iron are kept at high values during the oxidation period, by the addition of iron ore. A cessation in the addition of the ore, coupled with the maintenance of high temperatures, results in the reduction of the iron content of the slag with an attendant increase in the silica content thereof.

When the silica content passes a certain limiting value¹⁷, silicon and manganese begin to be reduced and pass into the steel, and are available for bringing about a deoxidation of the metal. In the best practice, this stage of the reactions is reached and maintained for some time previous to tapping. It cannot, perhaps, be said that it is established that even under such conditions, deoxidation is obtained to the extent which is really desirable. The ingot shown in Figs. 3 and 4 was produced from an acid Siemens-Martin steel charge, which fulfilled the best conditions according to present views.

It will be clear from these observations that, compared with the acid open-hearth process, the basic open-hearth process falls short in not giving equal facilities for deoxidation.

ELECTRIC STEEL MAKING PROCESSES

Force of circumstances and intrinsic advantages have resulted in the electric arc furnaces (either Heroult or Greaves-Etchell) being extensively utilized in Sheffield for the production of special steels. This process, controlled in the best technical manner, is ahead of any other process as regards the excellence of the steel produced. It is admirably adapted for the production of steels rich in special elements. The hearths are basic-lined, and after the scrap is melted, the first slag, which is rich in oxide of iron, is removed. A refining slag, essentially lime, is then produced, and under this slag, refining is effectively achieved. Steels made by this process need not have a sulphur or phosphorus content exceeding 0.01 per cent, and if deoxidation is continued to the desirable stage, the steel is remarkably free from "inclusions." Care is always taken not to over-heat the bath under the oxidizing slag, since otherwise gas troubles are caused, which are extremely difficult to eradicate. With suitable electric furnace equipment, and without undue haste in process, the quality of product obtainable is remarkable. The author anticipates great extension in the production of electric steel.

NONMETALLIC INCLUSIONS AND GASES FOUND IN STEEL

The nonmetallic inclusions found in all steels are now re-

¹⁷McWilliam and Hatfield, *Journal*, Iron and Steel Institute, Vol. 1, 1902.

ceiving attention both in America and in Europe. It is realized that they militate against the fullest advantage being taken of the intrinsic mechanical characteristics of the material. In the first place, they tend to form, when segregated, definite weaknesses in the otherwise strong and ductile material; in the second place, they tend to affect the form and orientation of the final constituents. In the former case, we notice "ghosts" exaggerated at times to form actual discontinuities; in the latter case, the effect is to be seen in a lessening of the ductility when tests are made other than coincident with the direction of deformation during fabrication. They consist of two types; "sulphides" which are the direct result of the amount of sulphur in the steel; hence the desirability in the acid processes of using materials of the lowest sulphur content, and in the basic processes of reducing the element to the lowest values possible under the circumstances. The composition and time and manner of the formation of the sulphides finally found in the steel form the subject of an important research at present being conducted by Dr. Andrew of Glasgow for the Ingot Committee of the Iron and Steel Institute. The full discussions which led to the institution of that investigation disclosed such an unsatisfactory state of knowledge in this field that the author considers there is little that can meanwhile be usefully stated. It would, however, appear that the manganese added to the liquid steel results in the formation of insoluble sulphide of manganese, most likely containing residual sulphide of iron. To what extent this manganese sulphide joins up with the silicate inclusions is not known.

The other type of inclusion, which apparently is governed by the physical chemistry of the steel-making process, might be designated "slag and oxide inclusions." It is largely held that they are traceable to the oxygen content of the liquid metallic bath.

It is held that if a slag containing oxide of iron is superimposed on a bath of liquid iron, some oxide of the iron will go into solution in the metal. It is not known, however, to what extent the presence of carbon and other elements in the bath affect the equilibrium value for oxide content, and this knowledge is necessary before present accumulating knowledge can be applied to steel-making processes. Austin¹⁸ seems to have satisfactorily

¹⁸Mr. Austin, *Journal*, Iron and Steel Institute, Vol. II, 1915, p. 157.

established that pure liquid iron can take up 0.24 per cent of oxygen, and Tritton and Hanson ¹⁹ established that liquid iron at 2785 degrees Fahr. (1530 degrees Cent.) would take up 0.21 per cent of oxygen, and C. H. Herty²⁰ and his collaborators have shown that the solubility increases to 0.304 per cent at 2910 degrees Fahr. (1600 degrees Cent.), and 0.452 per cent at 3090 degrees Fahr. (1700 degrees Cent.). The latter workers indicate that in calcium-iron oxide slags, the content of lime may vary over a wide range without affecting the solubility of the oxygen. Thus, in the absence of carbon, a definite solubility of FeO of some magnitude appears to be determined. C. H. Herty and J. M. Gaines²¹ claim and the author agrees with them, that since the solubility of the oxygen is greater with the temperature, that does point to the oxygen being present as a compound and not in simple solution. Tritton and Hanson give a value of 0.05 per cent oxygen as representing the maximum solid solubility. Much of the large tonnage of mild steel that is made, is tapped with the slag rich in oxide of iron, and the manganese and silicon, alloyed with iron, are added in the solid form to the liquid steel as it issues into the ladle. Assuming, therefore, that oxide of iron is in solution in the liquid steel, the reaction with the manganese presumably produces insoluble manganous oxide, which must obviously be dispersed through the liquid in the ladle in an extremely fine state of division. The silicon also added, should produce insoluble silica. The present view is that thus the manganous silicate is produced from the union of these two oxides, which has been considered to constitute what is believed to be the most serious form of non-metallic inclusion. The incompleteness of knowledge on this subject, however, is illustrated by the fact that the work of J. H. S. Dickenson²² disclosed that some of the silicates, isolated from acid open-hearth steel, did not consist entirely of manganous silicate, but were most probably really a double silicate of manganese and iron. Dickenson separated the inclusions from the steel by dis-

¹⁹F. S. Tritton and D. Hanson, "Ferrous Alloys Research," *Journal, Iron and Steel Institute*, Vol. CX, No. II, 1924, p. 90.

²⁰C. H. Herty, Carnegie Institute of Technology, Mining and Metallurgical Investigations, Bulletin 34, 1927, pp. 1-66.

²¹C. H. Herty and J. M. Gaines, American Institute of Mining and Metallurgical Engineers, February, 1928.

²²"A Note on the Distribution of Silicates in Steel Ingots," J. H. S. Dickenson, *Journal, Iron and Steel Institute*, Vol. CXIII, No. I, 1926, p. 177.

solving away the metal in nitric acid. He obtained residues from several types of steel which disclosed very interesting results:—

The percentage weight of the slaggy matter in the steel was apparently of the order of 0.016 to 0.04 per cent. Colelough, in

Table I

Residue obtained by complete solution of normal samples	Per Cent			
	SiO ₂	MnO	FeO	Al ₂ O ₃
Large Ni-Cr steel ingot	49.0	41.5	1.9	9.5
Large Carbon steel ingot	40.5	28.8	18.0	11.5
Large Ni-Cr steel forging	53.7	40.2	4.7	trace
Large Ni-Cr steel ingot	55.0	33.0	14.5	1.6
15-cwt. Ni-Cr steel ingot	72.0	22.5	3.9	1.1
12-ton Ni-Cr steel ingot	54.5	40.9	4.1	..

discussing Dickenson's research, indicated that solution in 10 per cent H₂SO₄ gave a higher yield of slaggy matter, and his results are quoted in Table II.

Following Dickenson's method, the author has obtained the results shown in Table III.

It is, therefore, not quite clear as to what the nature of the reaction is between the added manganese and the oxygen which is held to be present in the liquid steel, or whether the inclusions necessarily originate as just suggested.

Clearly, however, it is reasonable to suppose that if the steel is "finished" in this manner, the amount of the silicate present in the finished steel will be influenced by the composition of the slag, since the oxygen content of the steel depends upon the equilibrium values. These comments apply to both the acid and to the basic processes when operated under the conditions as above described. We are indebted to Ledebur for first pointing out that the oxides, produced in deoxidation by the manganese and silicon, were not likely to separate themselves readily from the liquid metal²³.

It will be seen that an adequate handling of this problem demands satisfactory methods of determining, by analytical methods, not only the amount of oxygen in the steel, but also the form in which it occurs. It may exist as oxides of iron, manganese, silicon, chromium and other elements; largely occurring as silicates of variable composition; and it may also occur as the oxides of car-

²³Dr. Ledebur, *Stahl und Eisen*, Vol. 15, 1895, p. 376.

Table II

Solvent	10 Per Cent HNO ₃	10 Per Cent H ₂ SO ₄
Residue per cent	0.0147	0.0296
SiO ₂	48.9	41.4
FeO	18.9	17.2
MnO	32.1	41.2

bon, CO and CO₂. This latter view is discountenanced in certain directions, but the author considers the whole matter worth re-consideration.

The gaseous oxides of carbon cannot be considered, except along with the general question of the gaseous content of steel.

Knowledge here is extremely meager, as will be shown, and this is largely due to the difficulty experienced in devising suitable

Table III

Steel	Per Cent slaggy matter	SiO ₂	FeO and other oxides	MnO
Acid Siemens	0.034	48.2	3.1	42.0
Acid Siemens	0.036	60.5	4.4	30.7
Bessemer	0.065	63.0	4.0	33.0
Bessemer	0.034	46.0	2.0	52.0
Electric	0.05	51.0	34.0	15.0
Crucible	0.024	50.0	20.0	30.0

methods of determining the amount of oxygen present. So important is this matter that the author considers it desirable to review the evolution of the methods.

METHODS OF OXYGEN DETERMINATION

Many different processes have been used with this object, and they can be mainly classed under two headings:—

- (1) Methods to obtain a residue of oxides from the steel.
- (2) Methods where an attempt is made to decompose the oxides, with subsequent measurement of the gaseous products of the decomposition.

The process of Troilus²⁴ was one of the first in the field, and this consisted of treating the steel with a neutral solution of ferric chloride with the subsequent separation of an impure residue. This residue—sulphides, phosphides, oxides and silica—was

²⁴Dr. Troilus, *Jernkontorets Annaler*, Vol. XXXIX, 1884, p. 432.

weighed and allowances made for impurities. Eggertz²⁵ estimated oxygen by dissolving the steel in iodine and separating the non-metallic residue. The Pourcel²⁶ method [temperature indefinite, but probably about 1110 degrees Fahr. (600 degrees Cent.)] consisted of heating steel drillings in a stream of chlorine until all the iron was volatilized and driven off as ferric chloride. Schneider²⁷ used bromine as a solvent for steel in these determinations, and this reagent was also used by Wust and Kirpach²⁸. All these methods were very ably criticized by Oberhoffer, Keutmann, Scherer and Strauch²⁹, and by Oberhoffer, Keutmann, Hessenbruch, and Ammann³⁰ in 1925 and 1926. Bender³¹ appears to have been the first to use the hydrogen reduction process, which, with modifications, came to be known as Ledebur's³² method, and was used to a great extent by subsequent workers. In this process, drillings of the steel are heated in a current of hydrogen at a temperature of 1830 degrees Fahr. (1000 degrees Cent.), or thereabouts, and the resultant water vapor is absorbed and weighed. Pickard³³, McMillen³⁴, Austin³⁵, Oberhoffer³⁶, Schmitz³⁷, Cain and Pettijohn³⁸, and Rooney³⁹, all used this process in slightly varying forms. The disadvantage of the method is that it does not obtain the whole of the oxygen from the steel; Oberhoffer and his co-

²⁵Dr. Eggertz, *Polytechnique Journal*, Vol. 88, 1868, p. 119.

²⁶Pourcel, *Journal*, Iron and Steel Institute, 1882, pp. 509-518.

²⁷Schneider, *Oest. Zeitschrift für das Berg-, Hütten- und Salinenwesen*, XLVII, pp. 257-60.

²⁸Wust and Kirpach, *Chemistry and Industry*, 550A, 1922.

²⁹Scherer and Strauch, *Stahl und Eisen*, Vol. 45, 1925, pp. 1555-63.

³⁰Oberhoffer, Keutmann, Hessenbruch and Ammann, *Stahl und Eisen*, Vol. 46, 1926, pp. 1045-9.

³¹Bender, *Dinglers Polytechnisches Journal*, Vol. CCV, 1873, p. 331.

³²Ledebur, *Stahl und Eisen*, Vol. XV, 1895, p. 376.

³³Pickard, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. V, 1913, p. 70.

³⁴McMillen, *Iron Age*, Vol. XCI, 1913, pp. 308-9.

³⁵Austin, *Journal*, Iron and Steel Institute, Vol. 92, 1915, pp. 157-161.

³⁶Oberhoffer, *Stahl und Eisen*, Vol. XXXVIII, 1918, pp. 105-110.

³⁷Schmitz, *Stahl und Eisen*, Vol. XXXVIII, 1918, pp. 541-2.

³⁸Cain and Pettijohn, Bureau of Standards Publication No. 118, 1919.

³⁹Rooney, *Journal*, Iron and Steel Institute, Vol. 110, 1924, p. 122.

workers have shown that only oxide of iron is reduced with certainty, while silica remains unaffected and manganous oxide is only decomposed slowly after prolonged heating and passage of hydrogen. In 1909, Goutal⁴⁰, published a method whereby steel was dissolved in copper potassium chloride solution and the gases liberated from the steel were carried by a stream of nitrogen into an absorption train. In 1919, however, this method was shown by Cain and Pettijohn⁴¹ to be inaccurate. The Pfeifer-Schiessl⁴² method consisted of heating at 2100 to 2280 degrees Fahr. (1150 to 1250 degrees Cent.) the steel and withdrawing the gases presumed by them to be formed by reaction between carbon and oxides in the steel, by means of a vacuum pump. This method has been modified to the extent of melting the steel (with or without antimony and tin) by Baradue-Muller⁴³, Goerens and Pacquet⁴⁴, Jordan and Eckman⁴⁵ and Hessenbruch and Oberhoffer⁴⁶, and it is claimed that complete decomposition of the oxides of iron, manganese and silicon occurs under the correct conditions. The Dickenson⁴⁷ method is a reversion to solution of the steel, and consists in dissolving a piece in dilute nitric acid with subsequent treatment of the residue to remove carbon and silicic acid.

It will, therefore, be clear that no method has yet been devised which is completely satisfactory for giving the total oxygen, unless the method of withdrawing the whole of the gases from liquid steel be considered as such. This method, however, labors under the disability that it assumes but does not prove that under the conditions of the determination, the whole of the oxygen has come off. It is necessary also to devise a process for determining the amount of CO and CO₂ in the steel at ordinary temperatures, the great difficulty being to be sure that the gases taken really represent the conditions in which they exist in the steel.

⁴⁰Goutal, *Comptes Rendus*, Vol. 148, 1909, p. 988.

⁴¹Cain and Pettijohn, Bureau of Standards Publication No. 126, 1919.

⁴²Pfeifer and Schiessl, *Stahl und Eisen*, Vol. 44, 1924, p. 113.

⁴³Baradue and Muller, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. VI, 1914, pp. 216-230.

⁴⁴Goerens and Pacquet, *Ferrum*, Vol. XII, 1914-15, pp. 57-64 and 73-81.

⁴⁵Jordan and Eckman, Bureau of Standards Publication, 1925, pp. 445-482.

⁴⁶Oberhoffer, *Stahl und Eisen*, 1928, p. 486.

⁴⁷J. H. S. Dickenson, "A Note on the Distribution of Silicates in Steel Ingots," *Journal*, Iron and Steel Institute, Vol. CXIII, No. 1, 1926, pp. 177-96.

GASES IN STEEL

When one really considers the present position as regards knowledge, matters must be considered to be thoroughly obscure. Charpy and Bonnerot⁴⁸ found 30 per cent of CO in the gases extracted. Boudouard⁴⁹ found CO and CO₂ together with nitrogen and hydrogen, given off by merchant iron at 2010 degrees Fahr. (1100 degrees Cent.) This is confirmed by Belloc's⁵⁰ work. Baker⁵¹, as the result of a very prolonged and interesting research, gives the composition of the gases given off, as varying with the temperature, but agrees that they are always carbon monoxide, nitrogen and hydrogen; he also shows that sound steel free from blow holes, contains more gas than blown steel. According to Donaldson⁵² carbon monoxide and hydrogen predominate, the other gases being there in a total quantity of less than 2.5 per cent; he indicates that the presence of silicon and manganese decreases the carbon monoxide and increases the hydrogen. Stadelers⁵³ has similar views. Allemann and Darlington⁵⁴ consider the solubility of the gases in the steel is decreased by the presence of manganese, silicon, aluminum or chromium. McCance⁵⁵ considers the problem but omits to deal with the part played by hydrogen. In a later work, Baker⁵⁶ showed the gases to consist almost equally of carbon monoxide and hydrogen, but the quantity differs with the condition of the steel. Amsen and Willners⁵⁷ confirm this. Lobley and Betts⁵⁸ experiments are of interest. Braune⁵⁹ indicates that nitrogen is present and in the form of nitride.

⁴⁸Charpy and Bonnerot, *Comptes Rendus*, Vol. 152, 1911, p. 1247.

⁴⁹Boudouard, *Comptes Rendus*, Vol. 145, 1907, pp. 1283-4.

⁵⁰Belloc, *Comptes Rendus*, Vol. 118, 1907, pp. 244-5 and 145 and pp. 1280-3.

⁵¹Baker, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, 1909.

⁵²Donaldson, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, 1916.

⁵³Stadeler, *Stahl und Eisen*, Vol. 37, 1917, pp. 1075-7, and *Zeitschrift für angewandte Chemie*, 31, Ref. 168, 1918.

⁵⁴Allemann and Darlington, *Journal*, Franklin Institute, February, 1918, America.

⁵⁵McCance, General Discussion on "Occluded Gases in Metals," *Journal*, Faraday Society, November, 1918.

⁵⁶Baker, General Discussion on "Occluded Gases in Metals," *Journal*, Faraday Society, November, 1918.

⁵⁷Willners, *Jernkontorets Annaler*, Vol. 110, 1926, pp. 107-124.

⁵⁸Lobley and Betts, *Journal*, Iron and Steel Institute, Vol. III, No. 1, 1925, p. 225.

⁵⁹Braune, *Revue de Metallurgie*, 1907, p. 834.

Sieverts and Krumbhaar⁶⁰ indicate that nitrogen is taken up at a temperature of 2192 degrees Fahr. (1200 degrees Cent.) but not evolved again when the steel is heated in vacuum. The solubility at high temperatures is a matter of definite disagreement and in this respect the work of von Malitz⁶¹ and Sieverts⁶² should be compared. Sieverts studied the solubility of gases in molten metal and indicates that hydrogen increases in solubility with the temperature, which would be a remarkable fact.

Heroult⁶³ and Goerens⁶⁴ state that cold steels contain little gas, and that blow holes are formed by reaction between the carbide of iron and oxide of iron present. Johns⁶⁵ takes the same view. Parravano and Scortecce⁶⁶, Parravano and Del Turco⁶⁷ and Klinger⁶⁸ all consider that the reaction between the carbide and oxide is responsible for the carbon monoxide and carbon dioxide given off. The present author takes the opposite view, i.e., that this reaction does not account for the evolution of the gas which causes the blow holes. In an interesting paper Andrew⁶⁹ suggests the gases are in combination in the iron, while from Rosenhain⁷⁰ we have a suggestion that they are present in the under-cooled liquid film existing between the crystals. This latter view, of course, depends upon the existence or otherwise of the amorphous film.

Taking a general view of the matter, however, there is really no definite agreement upon the subject, except that quite a strong body of opinion is in favor of the reaction theory as regards the production of the carbon monoxide and carbon dioxide. Such a view, however, does not take into consideration the hydrogen con-

⁶⁰Sieverts and Krumbhaar, *Berichte Deutsche Chemiker Gesellschaft*, Vol. 43, 1910, pp. 893-900.

⁶¹Von Malitz, *Bulletin*, American Institute Mining Engineers, 1907, pp. 691-726.

⁶²Sieverts, *Zeitschrift für Physikalische Chemie*, L. XXVII, pp. 591-613.

⁶³Heroult, *Journal*, American Electrochemical Society, Vol. 17, 1910, pp. 135-7.

⁶⁴Goerens, *Metallurgie*, Vol. 7, 1910, pp. 384-5.

⁶⁵Johns, General Discussion on "Occluded Gases in Metals," *Journal*, Faraday Society, November, 1918.

⁶⁶Parravano and Scortecce, *Annali di Chimica Applicata*, Vol. 14, 1924, pp. 3-17, and *Chimie et Industrie*, Special No. 312, 1924.

⁶⁷Turco, *Atti. Acad. Lincei*, Vol. 32, II, 1923, pp. 373-6.

⁶⁸Klinger, *Stahl und Eisen*, Vol. 46, 1926, pp. 1245-54, 1284-8, 1353-6.

⁶⁹Andrew, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, 1911.

⁷⁰Rosenhain, General Discussion on "Occluded Gases in Metals," *Journal*, Faraday Society, November, 1918.

tent and there is undoubtedly unanimity of opinion as regards the proportion of hydrogen present. Any satisfactory explanation, therefore, of the evolution of these gases which produce the blow holes, must contain adequate explanation of the part played by the hydrogen.

Looking at the matter from the steel making point of view, there are two outstanding facts which should be taken note of and which can undoubtedly be confirmed by anyone. The first is that in the acid open-hearth process, whilst the oxide of iron is still at a high value in the slag, and, therefore, it is to be presumed according to a certain view that oxide of iron is in solution in the iron, samples can be taken from the bath which freeze perfectly solid and free from blow holes. The next point is that in the electric process, if the bath is over heated in the early stages of the process, the metal becomes so charged with gas that even 1 per cent of silicon is insufficient to prevent the evolution of gas on freezing.

The author's object in reviewing this phase of steel manufacture has really been to draw attention to the great need for a number of investigators to concentrate upon these problems. We know little of the extent of the solubility of the gases in question in the steels in this range of temperature, and we know little concerning the solubility of oxide of iron in baths of commercial steel, containing as they do, carbon, phosphorus and other elements.

TEMPERATURE MEASUREMENTS

The work done by the Bureau of Standards Committee and individual American workers is known to you, and it is therefore proposed to confine these observations to personal experience.

For liquid steel temperature determinations, it is usual to employ distance pyrometers of the optical type. The two chief types of optical pyrometer are, (1) the disappearing filament and (2) the Wanner polarizing type. The latter is probably the more popular instrument, but both are equally adaptable. The following remarks apply particularly to the polarizing type.

The Cambridge optical pyrometer instrument may be regarded as a photometer, in which, by simply rotating the analyzer attached to the eyepiece, a beam of selected monochromatic light from the hot body is matched in intensity against a beam of similar

light from an incandescent electric lamp. The current through the lamp is standardized for each instrument. The instrument has generally two ranges, 1290 to 2550 degrees Fahr. (700 to 1400 degrees Cent.) and 1650 to 3630 degrees Fahr. (900 to 2000 degrees Cent.), and for the latter range an absorbing screen is moved in front of the objective. If the instrument is used on steel in the open, the correction must be added for divergence from "black body" conditions.

It is proposed to consider the degree of accuracy of the instrument, given an ideal hot body and plenty of time in which to make the temperature observations. Such conditions may be obtained with the standard amyl acetate flame as the "hot body" and the instrument set up in the usual way as if for calibrating purposes. With constant setting of the ammeter, readings may not be regularly obtained with greater accuracy than plus or minus 0.40 degrees angular deflection. This is equivalent to plus or minus 3 degrees Cent. at temperatures 2370 to 2550 degrees Fahr. (1300 to 1400 degrees Cent.). At higher temperatures, the temperature scale on the instrument becomes more crowded, but it is considered that a rotation of the pointer through one angular degree at the higher temperatures, makes more difference to the intensity of the light seen through the instrument, than a similar rotation at the lower temperatures. This somewhat counteracts the crowding of the scale, and thus it is still possible to obtain an accuracy of about plus or minus 5 degrees Cent. Slight inaccuracies in the setting of the ammeter, which gives a measure of the filament current, will cause definite small errors in temperature measurements.

A check on the instruments is frequently made by comparison with a rare metal thermocouple; the hot junction of the couple is mounted in the face of a refractory disk, placed in an electrically heated tube, so that it may be sighted upon through the end of the tube with the optical instrument. Suitably placed diaphragms serve to obtain, as near as possible, black body conditions in the neighborhood of the heated disk.

An exact measurement of liquid steel temperatures is only possible under very precise conditions. In steel works the conditions are far from ideal, and are usually uncontrollable, so that,

at the best, the observations should only be considered as an approximation.

The author would now like to draw attention to the very important matters of determining and controlling the temperatures of liquid steel. The actual temperatures existing during the reactions are fundamentally important, and are dealt with in practice on empirically practical lines. The casting temperature is, however, so important as to be a determining factor. The temperatures of liquid steel are best determined by the optical pyrometer (generally the Cambridge) and the total correction for black body conditions at such temperatures is usually at present made uniformly 125 degrees Cent.

Probably the best conditions for temperature determinations, obtain during the teeming of ingots, or castings, from the ladle. There one has a steady stream of liquid steel. Fumes, caused say by the burning of washes used in the molds, etc., often interfere with the observations, sometimes seriously, but in general such effects clear away before the complete casting of each ingot, and a clear field is obtained for a sufficient length of time to take a reading.

In almost all cases, it is not possible to fill the field of the instrument when sighting on ladle streams, but it is considered that this has little influence on the observations, except that it makes it more difficult to match the two halves of the photometric field. Difficulties arise from polarization, caused by the curved surface of the stream, and failure to view the stream normally to the surface, and also the possible chilling of the outside layer of metal, may introduce further errors. It has been concluded by Greenwood⁷¹ that the errors due to both these causes are not usually more than 20 degrees Cent., but that under certain conditions, they may reach 40 degrees Cent. In each of these cases, the effect is to lower the observed temperature. It has been noted that when the ladle stopper is not full open, the stream, instead of being steady and of uniform cross section, becomes straggly, and in reality consists of a number of separate fine streams. In such cases, the apparent temperature rises to the extent of 10 to 20 degrees Cent., and this is considered to be due to inter-reflection of

⁷¹Greenwood, *Journal, Iron and Steel Institute, Carnegie Scholarship Memoirs, 1923.*

light between the various component parts of the stream, so that the conditions are not truly free radiating.

The observation of the temperature of tapping streams from open-hearth furnaces presents no great difficulty. The steel is usually sighted upon as it passes over the end of the launder. Fumes do not interfere to any appreciable extent.

It is essential that readings be made on the center of the side of the stream exposed to view, in order to obviate possible effects of polarization. Usually the lower part of the stream appears hotter when viewed from the side, probably because of reflection from the molten metal of the falling stream, and from the surface of the metal in the ladle. The temperature of the metal issuing from the furnace is not usually constant from start to finish, and in some cases fairly wide variations occur. In order, therefore, to obtain a true indication, it is necessary to take the average of a number of readings. Temperature observations of the slag during tapping, may be taken, but they are considered to have no great value.

It is considerably more difficult to obtain a true indication of the temperature of the stream issuing from an electric furnace. As in the previous case, it is usual to attempt to measure the temperature as the stream passes over the launder, but as the contents of a small furnace are emptied into the ladle in about half a minute, the smartness of the operator is tested to the utmost. In addition, there are apparently, at times variations in temperature between the different portions of the steel forming the heat. It is impossible for an operator to tabulate a series of temperatures at time intervals, and the best that one can do is either observe the temperature of the hottest portion, or attempt to give an average value. The latter method introduces the human element to a definite extent, whilst the temperature of the hottest metal may or may not bear any definite relation to the average temperature. Further, in the case of the electric furnace, the slag comes over with the steel, and it is a very easy mistake to confuse the one with the other when sighting through the instrument. To minimize the chances of sighting on slag, the best position for the operator is either underneath the stage, towards the side of the slag pit (a very risky position, not always possible) or to the rear of the stream by the side of the furnace, sighting on the underside of the

stream in each case, but in these positions, there is the possibility of getting a false reading, on account of reflections from other portions of the stream, and from metal in the ladle. An alternative position is by the side of the stream. Fumes may interfere to a greater extent than in the case of tapping open-hearth furnaces. It is considered that observations on electric furnace tapping streams are generally unreliable, although in some cases, when exceptional conditions obtain, the observer may be confident of his results.

Johns⁷² and Greenwood⁷³ have observed that when teeming steel into two or three molds through a trough, the apparent temperature of the "clean area", on the trough-surface near to the falling stream, is the same as that of the stream itself, but as the field is shifted further toward the end of the trough, the apparent temperature rises, owing to the growth of a surface film having a higher emissivity. It is claimed that the presence of readily oxidizable elements, such as chromium, accentuates this effect. The average difference between the apparent temperatures of trough surface and ladle stream is 25 to 45 degrees Cent. Greenwood also compared the apparent temperature of the ladle stream with that of the surface in the mold, in which fresh metal is continuously exposed, and cooling at a minimum. He found that the stream appeared lower than the plane surface by an amount varying between 10 and 65 degrees Cent. It was claimed that the rise in apparent temperature is again due to the presence of a surface film of oxide. These casts contained 0.5 to 1.5 per cent chromium. It might be suggested that the apparent temperature of a plane surface is the correct one, and that the ladle stream gives low readings, but that this is not so has been shown by comparing the actual observed drop in temperature of the steel when run into the ladle, with the calculated drop in temperature. Greenwood calculated that the temperature should be lowered by 30 degrees Cent. The apparent loss in temperature as measured on (a) the ladle stream and (b) the trough surface, was 30 and 70 degrees Cent. respectively. The readings on the trough surface were therefore concluded to be high.

It is when one attempts to obtain a true indication of liquid

⁷²Johns, *Journal*, Faraday Society, 1918, 13, pt. 3.

⁷³Greenwood, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, 1923.

steel temperatures, whilst the steel is still in the melting furnace, that the greatest troubles are encountered. These are mainly caused by the variability of furnace conditions.

Considering the open-hearth furnace first, access to the steel itself is impossible, and observations may only be made on the surface of the slag, or on some part of the brickwork of the furnace interior. It is obvious that unless the conditions of working are constant from heat to heat, no definite relation between the apparent temperature of the slag or brickwork can exist. Actually, by altering the working conditions, it is possible to obtain the slag either hotter or cooler than the bath of steel. In addition to this, for the readings on the slag surface to be of any value, the conditions under which they are made must be reproducible, and this is by no means a simple matter.

Among the conditions which influence the apparent temperature of the slag surface in the furnace are the following:—

1. *The variable departure from black body conditions caused by the opening of the door.* The area near to the door will be most affected, and so much so, that Johns has stated that with the gas off, the conditions closely approach to that of a free radiating surface. Away from the door, the effect gradually diminishes with distance.

2. *Reflection from the brickwork and flames.* The apparent slag temperature may be increased or decreased by radiation from the brickwork, depending upon (a) their relative emissivities and (b) their relative temperatures. With gas on, the apparent temperature of the slag is increased by reflection, both direct from the flames, and indirect from the walls.

Greenwood has carried out an extensive study of the effect of reflection from flames, upon pyrometric observations, and he concluded that the average difference of temperature of the slag, with gas on and off, is 32 degrees Cent. correct to ± 10 degrees Cent. in 88 per cent of the cases. Our experience approximately confirms this average difference, but we are of the opinion that there is an even greater variation than Greenwood found. It is considered wise to eliminate the effect of flames, by making observations during reversals, when the furnace is clear for a brief period. Unfortunately, this limits the frequency of useful observations to

that of the reversals, i.e., about every 20 minutes, towards the end of a heat.

3. *The position of the field and viewing angle.* A constant field and viewing angle should be adhered to, to ensure comparative readings. The temperature of the extreme ends of the furnace fluctuates with the direction of the gas, so that observations should preferably be made through the center door.

It may be considered that much has been said with regard to the use of the optical pyrometer, but as hitherto it has provided the only quantitative manner of dealing with the temperatures of molten steel, it was felt desirable to discuss its limitations thoroughly. It fails, not so much in its utility for ensuring consecutive similar temperature effects in an individual works when the observations are made by one operator, but rather loses its value when attempts are made, as is being done at present, to provide essential data of universal application, derived from a number of different works. The manner of use is so important in its bearing upon the figures given.

Fortunately, from the practical point of view, the skill of the best melters, in empirically judging, not only the temperature throughout the process, but also the finishing temperature, is so considerable as to enable the reproduction of standard conditions a practical accomplishment. The difficulty is that until the pyrometry of high temperatures is more developed, the effect of temperature cannot be stated in a sufficiently quantitative way. The melters "instrument" is provided for him in the slag, the composition and temperature of which he controls, and thus by studying its physical characteristics and general appearance, he has a very good guide. The behavior, too, of the refractory materials of which his furnaces are constructed is also a valuable guide.⁷⁴

Attempts have been made from time to time to develop and apply the thermocouple method, but much more work is still necessary.

From the practical point of view, spoon samples are taken, of

⁷⁴Fusion "points"—

	Degrees Fahr.	Degrees Cent.
Fireclay	2910-3130	1600-1720
Silica	3000-3090	1650-1700
Magnesite	3630-3810	2000-2100
Chromium	3520-3720	1950-2050
Bauxite	2910-3270	1600-1800
Zirconia	4350-4710	2400-2600
Alundum	3720	2050
Carborundum	decomposes at 4060	2240

various sizes, from the liquid metal bath and judged in various ways. The normal sample after cooling out, is studied for the characteristics of the metal and slag, and provides much useful information.

A larger spoon sample is sometimes employed and the behavior of the surface of the liquid steel studied. The "mirror" test, so called from the appearance of the liquid metal surface, is valuable since the length of time the "mirror" surface is retained, does give at least an empirical idea of the temperature of the steel in the furnace; unfortunately the practical conditions demand absolute uniformity of the conditions, particularly as regards the temperature of the spoon.

It will, however, be perfectly clear that the serious attention of technologists must be directed to this question of taking quantitative observations of temperature.

INGOT MAKING

The characteristics of the ingot determine to a large degree the homogeneity and reliability of the ultimate product. The liquid steel is poured into the mold and freezes. It is indicative of the present state of knowledge that simple though the mechanism of the freezing may appear, yet it is a fact that the knowledge of the operation of physical laws and of the modification of the physical characteristics of iron and its alloys at high temperatures, are not sufficiently complete to enable a final and satisfactory picture to be drawn of the actual process of the freezing of the ingot. Until such an understanding is obtained, technical achievement, as regards the quality of ingot, is limited. This position of affairs was realized in Britain some few years ago, and an influential Iron and Steel Institute Committee is at work composed of representatives of the steel industry, of science and of the services. Two reports have already been published, to which reference should be made.⁷⁵ Some thirty-two steel ingots, varying in weight from 14 cwts. to 172 tons, have been studied. These ingots have been sectioned, and the nature of the distribution of the various elements determined, the degree and form of segregation, and the form of internal cavity, whether due to shrinkage or to the evolution of gas disclosed.

⁷⁵Report of the Committee on Heterogeneity of Steel Ingots, *Journal*, Iron and Steel Institute, 1923 and 1928.

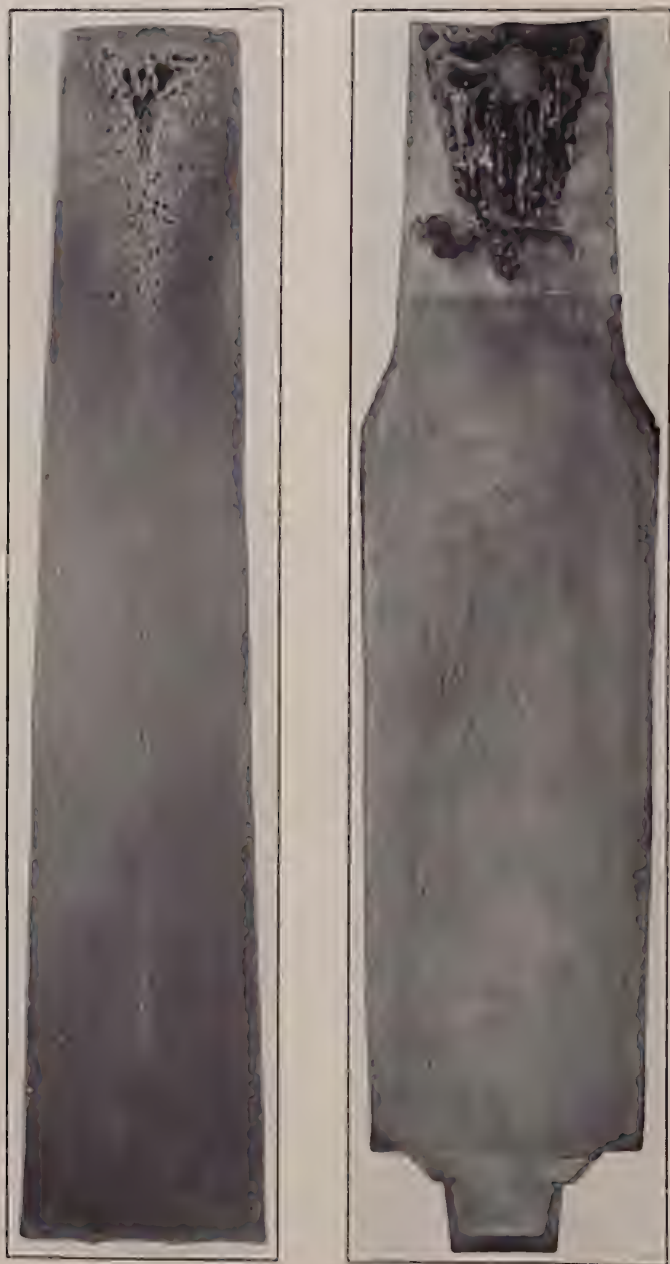


Fig. 2 (left)—Photograph of a Carbon Steel Ingot Representative of Ingots Produced Prior to the Increased Appreciation of the Effect of Design of Molds Upon Characteristics of the Interior of the Ingot. Fig. 3 (right)—Photograph of a Typical Medium Sized Ingot Studied by the Committee. This Ingot was Cast in a Chill Octagonal Mold.

An adequate knowledge of the mechanism of the extraction of heat from the freezing steel by and through the mold cannot be properly understood until the physical constants of the mold material, bearing upon the matter, have been determined for the temperatures involved. Enough has already been said to indicate clearly how extremely complex are the phenomena with which one has to deal in endeavoring to provide a reliable picture of the freezing of the ingot; and it is clear, therefore, that both the design of the ingot and of the mold has been heretofore, and is, indeed, even at the present time, definitely empirical. However, much progress has been made, and this can best be exemplified by examples drawn from the reports of the committee before referred to.

Fig. 2 is a photograph of a carbon steel ingot made many years ago, which was studied by the Committee as being representative of an extremely large tonnage of the ingots which used to be produced prior to the increased appreciation of the effect of design of mold upon the characteristics of the interior of the ingot. It was cast from the bottom in an octagonal chill mold tapering from $14\frac{3}{4}$ inches across the flats at the bottom, to $10\frac{1}{2}$ inches across the flats at the top. The mold was close-topped and for the greater part of its length was 3 inches thick.⁷⁶ The weight of the ingot was 23 cwts. It will be seen that the major portion of the cavity is contained in a space within a foot of the top of the ingot, but that small shrinkage cavities extend down the whole length to within 12 inches from the bottom. As regards the production of ingots from properly "killed" or piping steel, the Committee found that ingots are now being almost invariably produced with the broad end at the top, the narrow end at the bottom, with adequate arrangements as regards refractory lined feeder heads for ensuring the feeding of the ingot proper free from defects.

Solid carbon and alloy steel ingots produced from "piping" steel, and non-solid ingots typical of the large tonnages of mild steel, have been studied. Typical examples of this work will shortly be given, but the author would here like to indicate some of the encountered difficulties in the way of the solution of the general problem, particularly from the quantitative point of view. A

⁷⁶Example 32, Report of the Committee on Heterogeneity of Steel Ingots, *Journal*, Iron and Steel Institute, May, 1928.

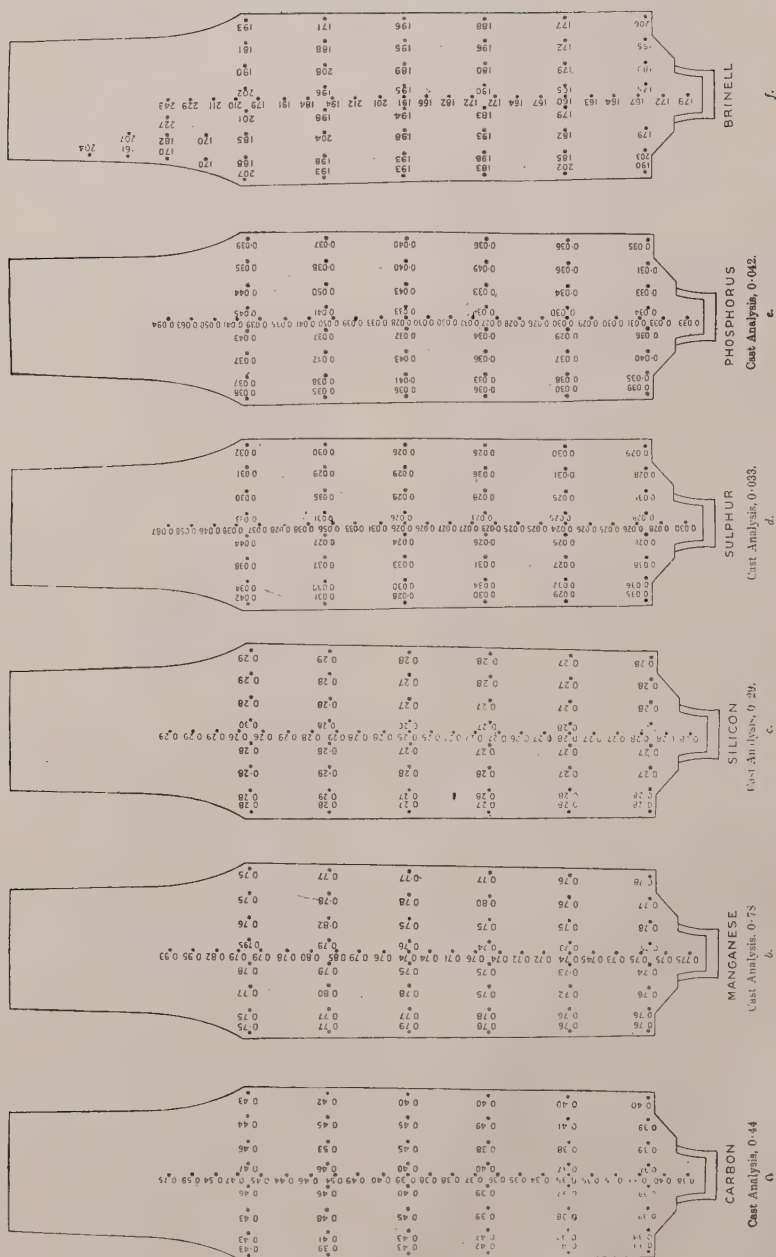


Fig. 4—Illustration Showing Chemical Analyses at Various Points on the Ingot Studied.

typical instance may be given in that it was necessary to explain the pure zone of steel occurring toward the bottom of the ingot along the central axis. Various explanations had been put forward; one school of thought considered that as a result of differential freezing, crystallites of steel, purer than the remaining liquid steel, fell and accumulated toward the bottom of the ingot. Careful consideration of data extant clearly showed that although it had long been held that the change over from the liquid to the solid state was accompanied by a definite increase in density, yet such a view is at the moment only surmise. Researches are being conducted both by Dr. Benedicks in Stockholm, and by Professor Desch in Sheffield, to settle the matter. Another school of thought based its explanation upon the effect of the temperature gradient upon the concentration of the solute in the liquid steel from the central axis to the freezing wall, i.e., the Soret effect; but our knowledge of the quantitative value of this effect in liquid steel is unknown, whilst, incidentally, the experimental method of determining the temperature gradient still remains to be worked out; and it is required to devise some means of providing the data for plotting the increase in thickness of the freezing walls of the ingot against time.

The change in the viscosity of liquid steel with falling temperature is not known. The liquidus and solidus of each type of commercial steel, as a result of the committee's investigations, has for some time been the subject of research under the direction of Professor Andrew of Glasgow. The effect of differential freezing cannot be envisaged in the absence of such data.

As typical of medium sized ingots of this class of steel studied by the Committee, a 25-ton ingot dealt with in the First Report can be instanced.⁷⁷ (Figs. 3 and 4). This ingot was cast in a chill octagonal mold, the weight being 24 tons 17 cwts., and it measured 43 inches at the top of the chill and 40 inches at the bottom. In considering the results of the investigation of this ingot, it is interesting to be able to state that information was supplied to the Committee which is very helpful. The steel was made in the acid open-hearth and the SiO_2 content of the slag was 56.5 per cent at the time the additions of manganese and silicon were made in the furnace. No aluminum was used. The steel on leaving the fur-

⁷⁷Example 12, First Report of the Committee on Heterogeneity of Steel Ingots, *Journal, Iron and Steel Institute*, 1926.

nace, had a temperature of 2894 degrees Fahr. (1590 degrees Cent.) and at the time of teeming into the mold had a temperature of about 2804 to 2813 degrees Fahr. (1540 to 1545 degrees Cent.). Eighteen minutes were taken in filling the mold, the average speed being at the rate of 1.393 tons per minute. The ingot was sectioned along its central axis and the section thus obtained was ground and polished. In this condition the chill portion of the ingot was free from shrinkage cavity, with the exception of perhaps a little looseness of structure coincident with the upper portion of the axis. As a result of etching with 5 per cent nitric acid in water, the nature and orientation of the segregate was disclosed as illustrated in Fig. 3. This section was subsequently drilled at various positions and the composition determined as disclosed in Fig. 4. Here, therefore, is an indication of the type of heterogeneity which exists in a 25-ton ingot when cast under what must be considered extremely satisfactory conditions from the standpoint of our present knowledge of the physical chemistry of the acid open-hearth process.

In Figs. 5 (a) and (b) and 6 (a) and (b) will be found illustrations relating to two very interesting ingots cast from nickel-chromium steel.⁷⁸

They were intentionally prepared from the same electric furnace heat. The cast weighed 8 tons 10 cwt., and four ingots were cast, all in molds of the same design. They were numbered A, B, C and D in the order of teeming; ingot B was selected as Example 19 and Ingot D as Example 20. At the moment of tapping, the steel and slag analyzed as follows:—

Steel	Per Cent	Slag	Per Cent
Carbon	0.29	SiO ₂	20.74
Manganese	0.42	FeO	2.16
Silicon	0.27	Al ₂ O ₃	2.24
Sulphur	0.016	MnO	0.13
Phosphorus	0.015	CaO	61.42
Nickel	4.38	Cr ₂ O ₃	
Chromium	1.41	MgO	8.14

A reducing slag had operated for some time prior to finishing. The time taken to pour the steel from the furnace was 2 minutes 20 seconds. After 2 minutes 27 seconds had elapsed, the Ingot A was teemed over a period of 3 minutes 40 seconds with a

⁷⁸Examples 19 and 20, Second Report of the Committee on Heterogeneity of Steel Ingots, *Journal*, Iron and Steel Institute, May, 1928.

$\frac{3}{4}$ -inch nozzle. After a lapse of 18 seconds, ingot B was teemed in 3 minutes 40 seconds with a $\frac{3}{4}$ -inch nozzle. 25 seconds later the teeming of ingot C was commenced, and was finished in 3 minutes 55 seconds. A special double nozzle was being employed, and the last ingot D was therefore teemed, after a lapse of 50

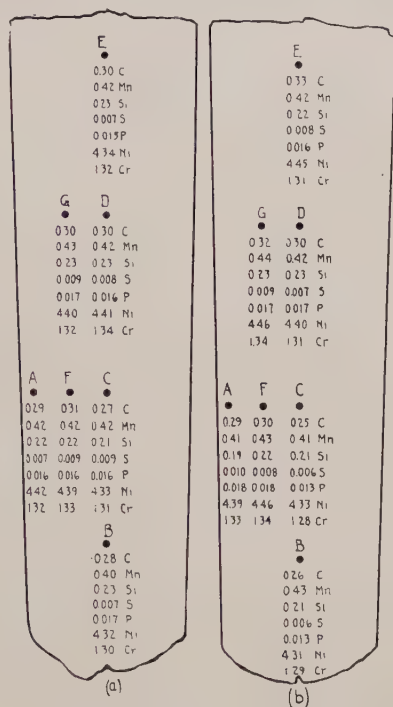


Fig. 5—Diagram Showing Chemical Analyses at Various Points on Two Nickel-Chromium Steel Ingots.

seconds, with a 1-inch nozzle over a period of 2 minutes 10 seconds. The temperature of the steel during tapping into the ladle was determined as 2903 degrees Fahr. (1595 degrees Cent.). The average temperature during the teeming of ingot B was 2894 degrees Fahr. (1590 degrees Cent.), whilst that of ingot D was 2822 degrees Fahr. (1550 degrees Cent.). It will thus be seen that ingot B was cast much hotter and with a smaller nozzle than ingot D, and as these were the only variables in regard to the two ingots, a comparative study is of interest. Owing to the composition of the steel resulting in pronounced air-hardening charac-

teristics, it was necessary to anneal the ingots before sectioning along the axis, and this was done by heating to 1562 degrees Fahr. (850 degrees Cent.), and then very slowly cooling down in the furnace. The feeder heads were then removed. After longitudinal sections had been prepared along the axis, exposing the exact central planes of the ingots, the surfaces were ground and polished and then etched with 2 per cent nitric acid in water. The macrostructures thus produced lent themselves indifferently to reproduction, so it was decided to reproduce the comparative crystal structures of the two sections. This was done by laboriously tracing from the macrophotographs the boundaries of the primary crystals, with the results shown in Figs. 6 (a) and (b). It was hoped that this comparative study would throw some light upon the mechanism of freezing.

It will be seen that in each ingot there is a well-defined outer layer of the first metal to freeze, consisting of very small crystals. Growing from this layer, in ingot B is the region of columnar crystals, which tapers off towards the top of the ingot. These columnar crystals are absent in ingot D. Two important central zones occur in both ingots, a zone of uniformly small crystals in the lower portion, and another of very large crystals in the upper portion. In the ingot D, cast at the lower temperature, the small crystals extend much higher up the ingot, and the zone of large crystals becomes much smaller, as, indeed, do the crystals themselves. It is appreciated that the crystals disclosed are probably pseudomorphs of the original crystals. Even the latter statement tends to be controversial, and it was not the intention of the Committee to discuss the theoretical implications of the data here disclosed. It was suggested that the outer shell of small crystals might be due to modifications resulting from the annealing process. Another ingot in the "as cast" state, and of the following analysis, was therefore selected:

	Per Cent
Carbon	0.31
Manganese	0.46
Silicon	0.27
Sulphur	0.014
Phosphorus	0.020
Nickel	4.19
Chromium	1.29

The ingot was of square section, 12 inches square at the top of the



Fig. 6—Photograph Showing Primary Crystals as They Were Traced from the Photomicrographs.



Fig. 7—Photograph of a Portion of the Fracture Made Across the Middle of the Ingot.

chill portion, and 10 inches square at the bottom; it was cast with a refractory-lined feeder head. This ingot was fractured cold, as shown in Figure 7, which is a large scale reproduction of a portion of the fracture made across the middle of the ingot. It will be seen that the existence of the outer zone of small crystals is confirmed, and that growing from these there is a layer of the columnar crystals. As a matter of interest one of the middle pieces of the ingot was used for further study. This piece of ingot was next annealed at a temperature of 1202 degrees Fahr. (650 degrees Cent.), and a transverse fracture obtained from the middle of the piece, with the resulting structure shown in Fig. 8. From this it will be seen that it is the primary crystallization which is still apparently responsible for the form of fracture.

These examples suffice to give an indication of the characteristics of carbon steel and alloy steel ingots, when produced from the type of steel which freezes solid, so essential in the production of highly stressed forgings and similar steel products.

In Figs. 9 to 12 two examples of ingots are quoted from the Second Report of the Committee, which illustrate the characteristics of the interiors of ingots representative of the very large



Fig. 8—Photograph of the Transverse Fracture of the Piece of Ingot After Annealing at a Temperature of 1202 Degrees Fahr. (650 Degrees Cent.).

tonnage of mild steel material used for general purposes. The ingot illustrated in Figs. 9 and 10 is an ingot of mild basic steel⁷⁹ of what is known as the rimming type. This steel on leaving the furnace, had the high temperature of about 2975 degrees Fahr. (1635 degrees Cent.). It will be noticed that no attempt is made to feed this type of ingot solid, and that evolution of gas during freezing is largely responsible for preventing the formation of pipe. The macro-etching of the section of the ingot in Fig. 9 (a) clearly indicates the distribution of the gas holes, and quite clearly, in steel of this type, owing to the high temperature at which it is worked, and the carbon content, these holes are expected to weld up. The sulphur print shown in Fig. 9 (b) discloses the interest-

⁷⁹Example 24, Second Report of the Committee on Heterogeneity of Steel Ingots, *Journal, Iron and Steel Institute*, May, 1928.



Fig. 9—(a) Photomicrograph of a Section of the Ingot Described Showing Distribution of Gas Holes. (b) Sulphur Print Showing That There is a Definite Zone Containing Lower Sulphur Content Than the Remainder of the Ingot.

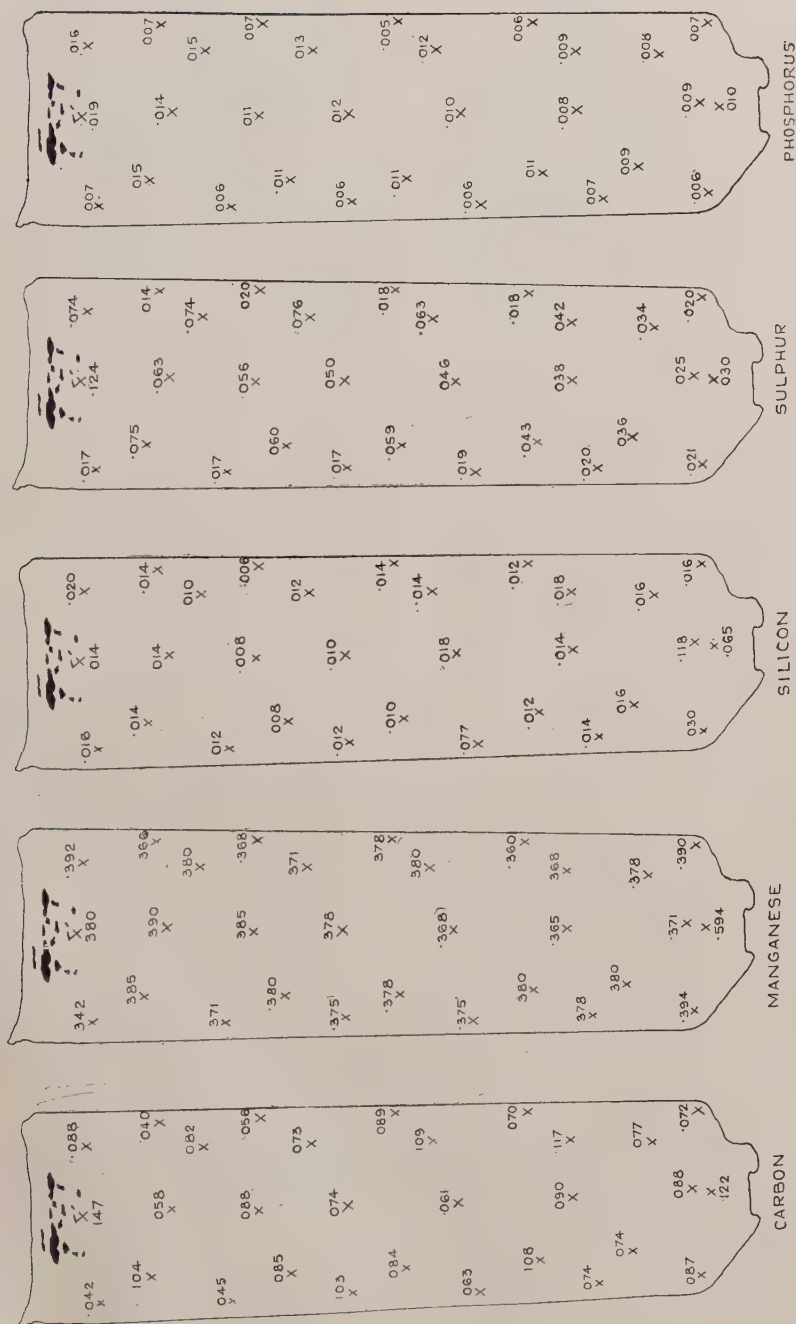


Fig. 10—Illustration Showing the Chemical Analyses at Various Points on the Ingot.

ing feature that there is a definite thick external zone of the ingot, in which the sulphur content is at a lower value than in the remaining portions of the ingot and this is confirmed in Fig. 10, also as regards the carbon and phosphorus contents. This particular ingot weighed 3 tons 1 cwt. The other example,⁸⁰ Figs. 11 and 12, is an ingot weighing 6 tons 15 cwts., of low carbon acid Siemens plate steel and here, in large measure, the same remarks apply.

As regards this type of steel which, it must be confessed, represents the bulk of the mild steel produced in all countries, whilst one cannot but appreciate the fact that owing to the excellent welding properties of such low carbon material and the economic considerations, the steel in the rolled condition with its high yield of the finished product, proves good enough for its purpose, yet one cannot but have at the back of one's mind, the hope that it may ultimately be found practicable to produce even this type of steel in ingots of the same high standard of characteristics as is found in the best type of forged ingots.

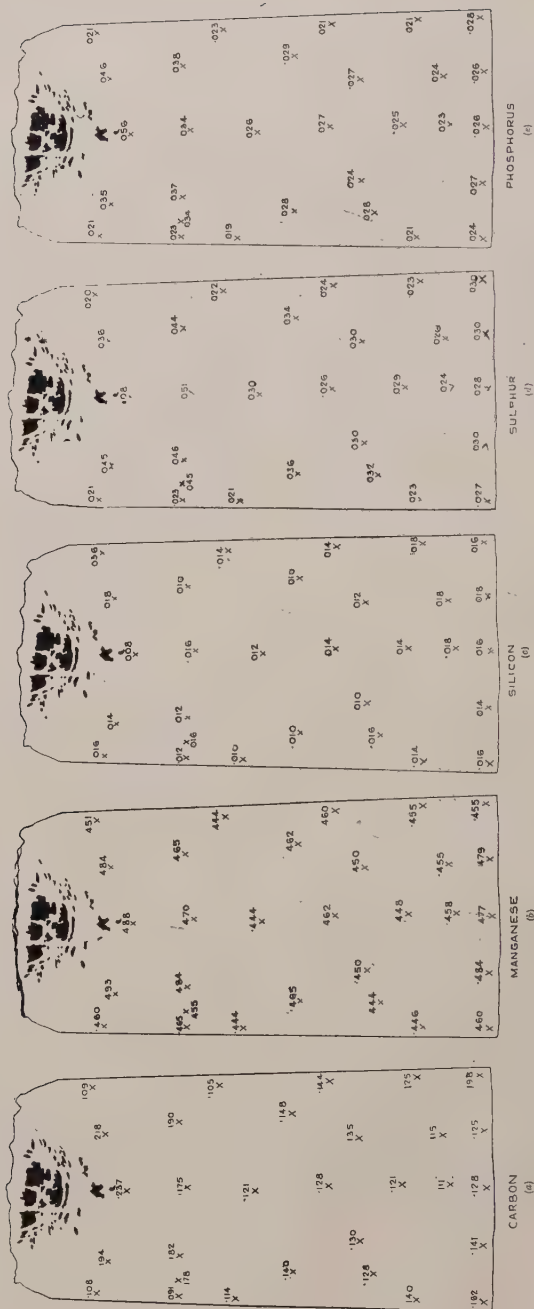
Generally reviewing the characteristics of ingots disclosed by the work of our ingot Committee, it may be said that when steel freezes it does so by a process of differential freezing. Consequently, no ingot is uniform in composition. This heterogeneity as regards composition is definitely found to increase with the mass of the ingot, so much so that in some of the largest ingots studied by the Committee, ingots weighing from 100 to 172 tons each, it can safely be said that the variation particularly as regards the carbon content, is so considerable as to necessitate the designing engineer taking into consideration the effect of the variation of the carbon upon the strength of the material. The sulphur and phosphorus were also found to vary within wide limits. As regards the special elements, it was found that nickel remained fairly constant through the mass of the ingot, chromium showed definite evidence of segregation, whilst molybdenum, where studied, showed a very definite tendency to segregate. However, without running to greater length, the author feels that he cannot do better than recommend anyone, interested in steel ingots, to read the Reports of the Committee, in which will be found, carefully stated, the results of the examination of some 32 ingots of varying types and sizes.

The Committee has decided not to attempt, for the time being,

⁸⁰Example 27, Second Report of the Committee on Heterogeneity of Steel Ingots, *Journal*, Iron and Steel Institute, May, 1928.



Fig. 11—(a) Photomicrograph of a Section of the Ingot Described.
(b) Sulphur Print of the Ingot Described.



a picture of the mechanism of freezing, and the author considers he will be wise if he adopts the same attitude.

One point can, however, be touched upon, and that is the undoubted fact that the higher the proportion of nonmetallie

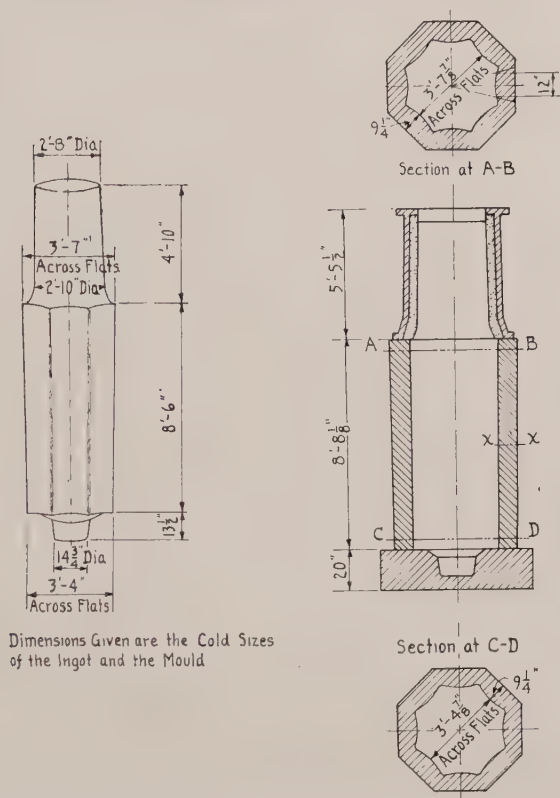


Fig. 13—Diagram of Ingot and Mold of Present British Design.

inclusions in the steel, i. e., sulphide, silicates and oxides, the more serious do the results of local segregation, i. e., ghosts, become. It is undoubtedly a fact that particularly when casting large masses, the sulphur should be kept as low as possible, and the steel should be produced by one of the processes which enables the deoxidation to take place in the steel making furnace to the maximum degree possible.

The casting temperature and speed of teeming should be thoroughly explored as regards any particular type of ingot, and

ing of large masses is rendered exceedingly difficult, owing to the influence of such a great number of factors, many of which cannot easily be determined. A mass of steel placed in a furnace is heated (1) by radiation from the walls of the furnace and from the hot gases or flames, (2) by conduction, and (3) by convection, including actual licking of the surfaces of the mass by the flames or hot gases passing through the furnace chamber. Surface combustion may also take place as well as surface reactions, (such as oxidation), which also produces heat and helps in supplying the heat necessary to bring the mass up to the desired temperature. All the factors mentioned above affect the rate at which the surface of the mass absorbs heat. Even if this information were available, the time required for the heating operation would be difficult to ascertain, since further knowledge as to the thermal conductivity, specific heat and density is necessary for the complete solution of the problem. The factors are not constant, but vary with the temperature of the material, rendering an exact mathematical treatment of the problem impossible. To complicate matters further, the heat of any transformation which might occur, materially affects the solution to some extent. Then again, the mass may be put into a cold furnace, or into one which is already raised to the desired temperature. These considerations are sufficient to indicate the complex nature of the problem.

However, in any effective steel works, practical usage and experience have resulted in tolerable procedure being adopted, but if such practice is critically examined, it will be found that convenience frequently dictates it. Ingots and blooms are not always given the discriminating time-temperature heating which theoretical considerations might suggest. Two considerations must be always before the operator. In the first place, the piece should be properly soaked through so that the optimum capacity for plastic deformation is attained; this will obviously be influenced by composition. In the second place, the time and the temperature gradient should be so regulated as not to produce overheating of the steel, or burning of the outer layers, otherwise oxide will penetrate fairly deeply along the grain boundaries as indicated in Fig. 15 (a) and (b) which show how nickel-chromium steel may be affected in this way. Excessive heating leads to the development of large grain size and sometimes, in such cases, to inter-

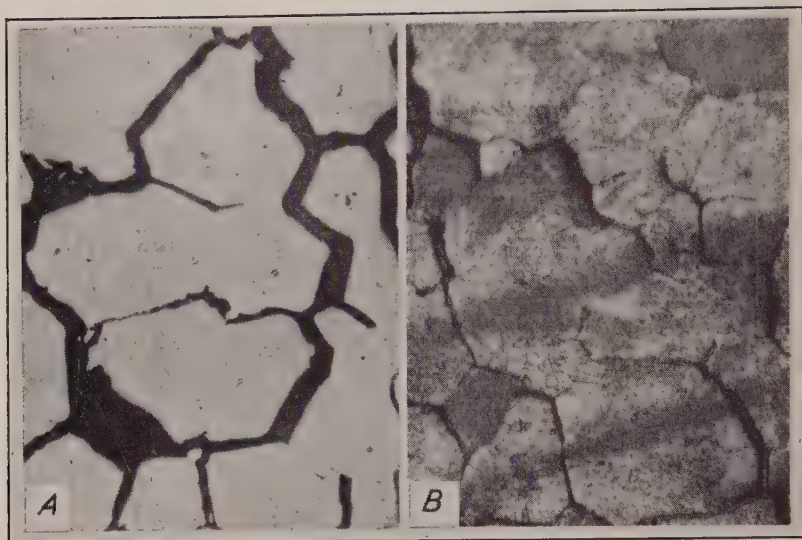


Fig. 15—Photomicrograph of Burnt Nickel-Chromium Steel. (a) Unetched. (b) Etched
 X 25.

granular weaknesses which will frequently persist even after hardening and tempering. Only a very complete understanding of the time-temperature effect will enable this type of trouble to be eliminated. Actual pyrometric studies, carried out on varying masses, are necessary to put this aspect of technique on a satisfactory basis.

A typical instance of such experiments may, perhaps, be usefully described, as carried out in the Firth works some time ago, viz., the heating up of a 30-ton ingot. The furnace used was coal-fired. A thermocouple was placed (1) in the furnace atmosphere, (2) on the surface of the ingot, (3) 12 inches inside, (4) 36 inches inside, (5) by means of an axial hole at the centre of the ingot. The temperatures were carefully recorded, and the data obtained disclosed in Fig. 16, enable sound deductions to be made concerning the necessary time-temperature treatment to obtain the uniform heating in such a mass, which is so essential. This experiment was intentionally based upon the using of a cold ingot, and it will be seen that the furnace had been reduced to a very low temperature before heating was commenced.

It is, of course, essential in handling very large ingots, to

transfer them hot to the forge furnace and subsequently to arrange the changes in temperature so as not to lead to the production of internal stresses with resultant possible internal damage to the forging. A comparison of modern practice, both as regards the

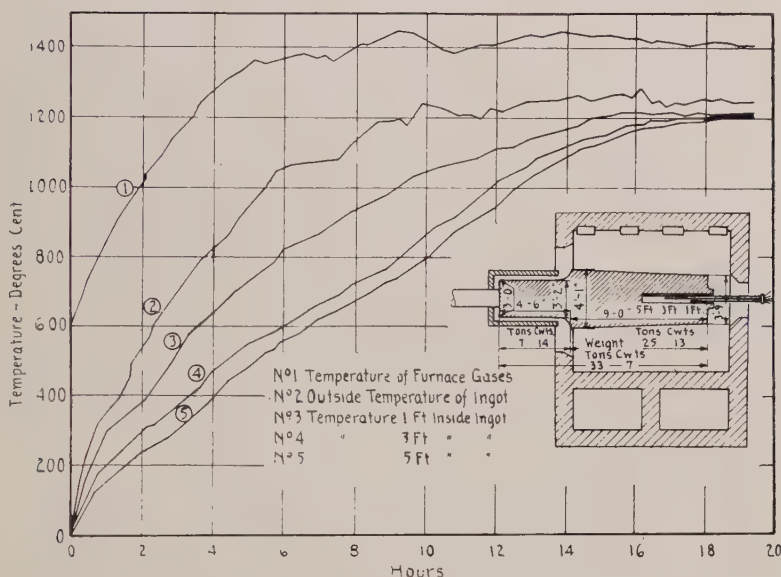


Fig. 16—Curves Showing the Rate of Heating of an Ingot at Various Points.

technique of ingot manufacture, and as regards the knowledgeable way in which the ingot and bloom are taken care of during manipulation, at once brings home to one how much more reliable large forgings necessarily are which have been produced under modern conditions. With the avoidance of unduly high temperatures at the commencement of forging, which prevents the impairing of the intrinsic properties of the steel, and the care which is taken not to deform the steel when the heat has fallen too low, thus preventing internal rupture and local work hardening, some of the more serious troubles are eliminated. One very important point to be watched is the question of symmetrical and uniform heating; if this is not achieved, the result frequently obtained in the final forging is distortion of a mischievous and subtle kind.

When considering small forgings, exactly the same problems occur, but upon a smaller scale, and the author strongly holds

Table IV
Forging Temperatures

Material	Suggested Maximum Forging Temperatures		Theoretical Burning Temperatures	
	Deg. Cent.	Deg. Fahr.	Deg. Cent.	Deg. Fahr.
1.5 per cent Carbon Steel	1050	1920	1140	2080
1.1 per cent Carbon Steel	1080	1980	1180	2140
0.9 per cent Carbon Steel	1120	2050	1220	2230
0.7 per cent Carbon Steel	1180	2140	1280	2340
0.5 per cent Carbon Steel	1250	2280	1350	2460
0.2 per cent Carbon Steel	1320	2410	1470	2680
0.1 per cent Carbon Steel	1350	2460	1490	2710
Silico-Manganese Spring Steel	1250	2280	1350	2460
3 per cent Nickel Steel	1250	2280	1370	2500
3 per cent Nickel-Chromium Steel	1250	2280	1370	2500
Air Hardening Ni-Cr Steel	1250	2280	1370	2500
5 per cent Nickel (Case hardening) Steel	1270	2320	1450	2640
Chromium-Vanadium Steel	1250	2280	1350	2460
High Speed Steel	1300	2370	1380	2520
Stainless Steel	1280	2340	1380	2520
Austenitic Chromium-Nickel Steel	1300	2370	1420	2590

that the utmost technical control is demanded and justified. The final heat treatment cannot always be relied upon to eradicate mishandling at this early stage. If steel is over-heated when heating for forging or rolling, the final mechanical properties of the steel are impaired. The liquidus and solidus of each type of steel should be determined, and the temperature should not be allowed to reach within 180 degrees Fahr. (82 degrees Cent.) of the solidus. Table IV gives an indication of the manner in which the permissible maximum heating temperature may vary for different steels.

Normalizing and Annealing

The terms "normalizing" and "annealing" are sometimes loosely applied to a variety of operations in a steel works. Steel in the forged or rolled condition has a nonuniform structure and is in a strained state, and in order to remove the stresses remaining from these operations, or, at any rate, to reduce them to a low value, it is necessary to reheat the material. This may be accomplished by either of the operations under discussion, but in addition to the necessity for reducing such stresses, it is necessary to modify the material by replacing the crystalline structure left by the hot work, with a refined one. The actual operation of normalizing consists in heating the steel above the Ac_3 point and allowing to cool in air free from draughts. Annealing is a much more thorough treatment, involving a knowledge of the behavior

of the various steels under varied conditions. The original method of annealing was to heat the steel to a high temperature, maintain that temperature for a varying time, and cool very slowly. This is quite satisfactory for many steels, but in some of the alloy steels better results are obtained by heating to temperatures below the carbon change point, and cooling in air or in the furnace. In any case, it should be understood that the residual stresses are less as the speed of cooling is less. It may be of interest to include the British definition of these terms:

Normalizing. Normalizing means heating a steel (however previously treated) to a temperature exceeding its upper critical range, and allowing it to cool freely in the air. The maximum temperature shall be maintained for about 15 minutes, and shall not exceed the upper limit of the critical range by more than 90 degrees Fahr. (32 degrees Cent.).

Annealing. Annealing means reheating, followed by slow cooling. Its purposes may be—

- (a) To remove internal stresses or to induce softness, in which case the maximum temperature may be arbitrarily chosen.
- (b) To refine the crystalline structure in addition to the foregoing (a), in which case the temperature used must exceed the upper critical range as in normalizing.
- (c) In the case of tool steel, to modify the structure by balling up the carbides by using a temperature near to the carbon change point.

Hardening and Tempering

For many centuries, swords, knives, and the like, have been hardened and tempered, and the “finely-tempered” sword, an article in past ages much in demand, was produced long before pyrometric observations and the science of metallography had explained the fundamental principles of such processes. In considering the hardening and tempering of steel parts for airplane and automobile work, we are only following the example of the time-worn procedure of the old cutlers and armorers. Now, be it noted, that a novice would never, in the old days, have been permitted to harden and temper, only the highest skill and

experience permitting the production of the desired results, and today the same remarks apply. There is quite enough scope in the art of hardening and tempering small and large parts, such as used in the various branches of engineering, to justify the growth of a class of operators with brains to understand and skill to execute the treatments required to obtain those excellent qualities which skillful hardening and tempering will induce. Bearing on this, it not infrequently happens that small parts are required in which one portion will have to be finely tempered and tough, whilst the other is quite hard, and even more difficult requirements can be met, providing the development of the necessary technique in the operator is insisted upon. In the whole range of steel metallurgy there is no direction where careful study and good technique can produce more valuable results.

The operation of hardening consists of quenching after raising the steel to temperatures above the critical points, at which it will exist as solid solution. In dealing with parts made of 0.3 to 0.4 per cent carbon and under, it is not sufficient to raise to a temperature at which the solid solution areas are formed from the pearlite, but the temperature must be attained at which the ferrite has also disappeared owing to its solution in the solid solution. The desirable temperature, therefore, for hardening, is that at which the steel is quenched as a completely homogeneous solid solution, and this temperature will depend upon the composition of the steel. If temperatures sufficiently high for this are not reached, we simply obtain residual ferrite, which reduces the effectiveness of the whole operation of hardening and tempering. Generally, temperatures from 1470 to 1560 degrees Fahr. (800 to 850 degrees Cent.) are quite sufficient for this operation, but the actual temperature depends upon the steel, and in this connection it is particularly important that the operator should appreciate the temperatures at which the changes take place in the given steel. It might be well here to caution against the use of too high quenching temperatures.

- (1) If the temperature is taken too high, and undue brittleness is introduced into the steel.
- (2) Quenching from higher temperatures naturally means greater internal stresses.
- (3) If too high temperatures are employed, the quenching

medium, if of limited volume, becomes heated to a greater temperature during the quenching operation, and is, therefore, less effective in quenching the material, the speed at which the article passes through the critical zone being most important.

While discussing hardening, it might be well to point out that rapid heating should, for obvious reasons, be avoided. The question of hardening cracks bears very directly upon reliability, and it might here once more be emphasized that carelessness in hardening and tempering may vitiate the results of most excellent insight and care in design. It will also be fully appreciated that in the hardening operation, rapid changes in section, sharp corners, angles, etc., are a disadvantage just as in other items of process to which reference will be made.

With regard to the medium employed for hardening, that is determined by the character of the steel, and may either be water, oil or air. The mass of the forging to be cooled has a great effect upon the rate of cooling, which is, of course, the controlling factor. It is customary to talk of "quenching" large forgings, but the term is only a qualitative one when so used. The author, on one occasion, made quantitative temperature observations during the quenching of a 25-ton forging in 100 tons of oil. The rate of abstraction of heat from the forging which, at 1562 degrees Fahr. (850 degrees Cent.), was placed in the oil, having a temperature of 122 degrees Fahr. (50 degrees Cent.), was such that it required 30 minutes time before the oil had steadily risen to 169 degrees Fahr. (76 degrees Cent.) and the forging had only cooled to a mean temperature of 932 degrees Fahr. (500 degrees Cent.). To harden a forging of such mass, throughout, in such a medium, requires the introduction of elements sufficient to render the "breakdown of the solid solution" so sluggish as to prevent its occurrence under that rate of cooling. The use of water when quenching large masses, is permissible, but demands a very high standard in ingot production and in the subsequent operations. On the other hand, air-hardening is not admissible in very large masses.

The tempering operation, resulting in the degree of softening required, depends upon the particular temperatures to which the hardened part is submitted, the reheating causing the breaking

Table V
Oil-Quenched from 850 Degrees Cent.

	Tempered 932 deg. F. (500 deg. Cent.)				Tempered 1022 deg. F. (550 deg. Cent.)				Tempered 1112 deg. F. (600 deg. Cent.)				Tempered 1202 deg. F. (650 deg. Cent.)			
	1 hr. 1 1/8"	1 hr. 2"	1 hr. 4"	2 1/2 hrs. 1 1/8"	1 hr. 1 1/8"	1 hr. 2"	1 hr. 4"	1 hr. 1 1/8"	1 hr. 2"	1 hr. 4"	3 1/4 hrs. 8"	3 1/4 hrs. 8"	1 hr. 1 1/8"	1 hr. 2"	1 hr. 4"	2 1/2 hrs. 4"
<i>Tensile.</i>																
Elastic limit, lbs./sq. in.	114,700	80,300	67,000	97,000	55,000	67,000	82,900	70,500	58,200	52,200	62,500	66,100	60,500	60,500	60,500	60,500
Yield point, lbs./sq. in.	144,900	114,900	81,500	117,800	103,800	81,100	100,800	95,600	76,500	62,100	82,400	83,300	68,300	68,300	68,300	68,300
Max. stress, lbs./sq. in.	152,500	128,300	101,000	129,500	120,600	99,200	115,400	112,600	96,800	88,200	107,500	103,300	90,700	90,700	90,700	90,700
Elongation, per cent.	15.0	20.0	23.0	21.0	21.0	23.0	24.0	24.0	25.0	27.0	26.0	26.5	26.0	26.0	26.0	26.0
Red. of area, per cent.	49.7	57.5	61.5	63.6	61.5	61.5	66.8	65.7	64.75	69.25	68.8	67.8	66.8	66.8	66.8	66.8
<i>Torsion.</i>																
Shear Stress at Elas. Limit, lbs./sq. in.	92,500	77,600	51,700	70,100	47,000	61,800	59,200	47,500	45,900	49,200	45,900	45,900	45,900	45,900	45,900	45,900
App. Max. Shear Stress, lbs./sq. in.	134,600	117,200	98,600	112,700	96,800	101,200	103,400	94,300	99,200	95,900	92,300	92,300	92,300	92,300	92,300	92,300
Prob. Act. Max. Shear Stress, lbs./sq. in.	101,000	88,100	73,900	84,400	72,100	75,900	77,600	70,800	74,600	72,000	69,200	69,200	69,200	69,200	69,200	69,200
Degrees twist	306	388	630	552	43	712	850	562	700	662	806	738	738	738	738	738
Izod Impact ft. lbs.	30, 31, 29.	25, 25, 24.	39, 35, 37.	52, 51, 54.	43	36, 33, 33.	62, 67, 59.	59, 58, 57.	55, 53, 58.	100, 102, 101.	76, 74, 74.	76, 74, 60.	76, 74, 60.	76, 74, 60.	76, 74, 60.	76, 74, 60.
Stanton Blows	12,535	4,966	1,809	6,620	8,490	2,176	6,770	3,023	1,473	3,110	2,605	1,716	1,716	1,716	1,716	1,716
Arnold reversals	228	228	210	232	248	246	236	244	226	252	278	246	246	246	246	246
Brinell Numbers	321	311	212	269	255	207	241	241	197	217	217	217	217	217	217	217
Carbon	0.29%															
Manganese	0.33%															
Sulphur	0.015%															
Phosphorus	0.011%															
Nickel	3.29%															
Chromium	0.52%															

*Based upon T. M. = $\frac{d^3}{12} \times \text{shear stress.}$

down of the hardened state of the steel. There is not time in this short section to discuss the theory of the matter, and it will perhaps be well to give a typical example of what the effect of tempering at various temperatures for various times in various sections, may be upon a specific steel, see Table V.

The question should be discussed as to whether it is desirable to quench from the tempering temperatures. The author does not hesitate to say that such procedure tends to leave residual internal stresses of considerable magnitude, in the parts so quenched. Such is, however, the frequent procedure for the sake of the higher notched bar impact figures so obtained. Alloy steels are now available, notably those containing molybdenum, which do not demand such rapid cooling to obtain a good notched impact value. In any case, however, there are notable cases, particularly in turbine work, where internal stresses arising from such causes, are particularly to be avoided.

Whilst discussing the question of tempering, the author feels that he should emphasize the merit of two papers recently presented by H. A. Dickie⁸¹ and J. H. Whiteley⁸² respectively, which point to changes in the matrix of such steels within that range of temperature, of a sufficient order to require very careful consideration. This relates to the degree of solubility of the carbide.

Effects of Forging on Structure and Properties

The processes of hot working steel by forging and rolling have for their object, not only the production of shapes suitable for the purpose to which the steel is to be put, but also modifications in the condition and properties of the resulting product. Steel as cast, possesses certain inherent weaknesses. Such weaknesses are a natural consequence of the manner of solidification. The process of crystallization of a large mass of metal is necessarily somewhat slow, and the resulting formation of relatively coarse crystals of varied composition and configuration, as previously discussed, leads naturally to variable mechanical and physical properties throughout the mass. In addition, a certain amount of looseness of structure, if not actual cavity, is necessarily left by reason of

⁸¹H. A. Dickie, *Journal*, Iron and Steel Institute, Vol. II, 1927, p. 223.

⁸²J. H. Whiteley, *Journal*, Iron and Steel Institute, Vol. II, 1927, p. 293.

the varying contraction effects during the cooling of the mass, which exist at all stages from the beginning of solidification down to a uniform final temperature. Even in a correctly designed ingot, which is a casting in which all efforts have been concentrated on obtaining the best results as regards uniformity and solidity, it is shown (in the section dealing with Ingots, Section II) that the final result is far from ideal.

The forging of the steel has the effect of modifying the crystalline structure, by breaking up coarse crystals and massive segregated constituents, and also of knitting together and, in many cases, actually joining up by welding, loosely cohering or separated parts of the mass. It is well recognized that substantial improvements can be effected in castings by heat treatment alone. Mild steel castings are in use for many parts which have to withstand severe conditions of service and by suitable annealing after casting, mechanical properties are obtainable which are almost equal to those obtained in a good forging. A simple example of this is a locomotive wheel center casting. The annealing process causes a diffusion of the constituents—mainly the carbon in the steel—so that the original coarse and acicular formation of ferrite and pearlite is replaced by a relatively fine and redistributed ferrite and pearlite structure free from the obvious large planes of weakness previously present. There are, however, even in a carbon steel, certain features of structure which persist after heat treatment, and these are, in the main, based upon the arrangement and distribution of the impurities present in the steel. Slag and other nonmetallic inclusions appear to provide centers for the predisposition of the configuration of the new system of crystallization. By forging the steel, this configuration is distorted, and to some extent broken up, and the original tendency to a coarse formation is thereby considerably reduced. There is also the further effect that the coarse crystallization, which is probably still present (as the gamma phase) after reheating for forging, is deformed to such an extent that recrystallization, while still in the high temperature zone, occurs on a finer scale, and by arranging for the finish forging to be at a satisfactory temperature, crystal growth has not time to take place. The final structure is, therefore, of a more refined order.

The presence and distribution of impurities in the steel do,

however, assert their influence to some degree, on the final structure, and it is essentially this which leads to "grain" or fiber in the finished article. The well known "banded" structure in mild steel bars or plates, is an instance where some impurities—chiefly nonmetallic inclusions, but probably also affected by constituents in solution which have not been evenly diffused during the reheating operations—have located the first precipitation of ferrite during the recrystallization on cooling down through the recalescence zone of temperature. Such structures naturally run in the direction where greatest deformation from the original ingot has occurred. "Grain" or fiber is not, however, always associated with inclusions. In numerous examples where the steel has different properties longitudinally and transversely to the direction of forging, the inclusions are small and not numerous. The essential explanation, in such cases, of this, is to be found in two directions, (1) the steel may contain constituents which do not readily go into solution and diffuse when heated to the forging temperature. Such constituents will then behave, during forging, in a similar manner to nonmetallic impurities, so far as their orientation in the forging is concerned. (2) The steel may be of such a character that the "coring" effect produced during primary crystallization of the steel, which comprises variations in the composition of the original crystals from center to outside, still persists in spite of deformation of the crystals, and in spite of long exposure to forging temperatures. Such differences in composition within the small areas of the crystals, may be of an extremely small order, and yet, owing to the extremely slow rate of diffusion in the solid, of the compounds concerned, no approach to uniformity may be obtained. The distribution of the micro-heterogeneity will, therefore, be that of elongated shapes in the direction of forging. Such effects appear to occur in many alloy steels such as 3 per cent nickel-chromium steel. The distorted shapes of what were apparently original dendrites in the "as cast" material, are frequently to be seen after macro-etching fairly large forgings.

The importance of "grain" is recognized practically, in many forgings, by the adoption of methods of carrying out the forging in such a way that the grain shall lie, in the finished article, in that direction most conducive to strength and capacity to resist the service stresses. The example of a crankshaft forged so as to

obtain the flow round the webs and crank pins, may be quoted. The correct forging of die blocks, gear wheels, spring plate eyes, etc., demands consideration of this feature. The great value of the drop forging process arises largely from the adaptability of this process to ideal arrangement of the "fiber" in the resulting forging.

It should not be imagined, however, that forgings have strength only along the grain. Actual data as to the comparative strength along and across the grain,⁸³ show that it is exceptional for the difference in strength in the two directions, as judged by Wohler fatigue tests, to reach 17 per cent. The differences in elastic limit, yield strength and maximum stress in the two directions, are practically negligible. There are, however, differences in ductility of a measurable order, and notably in Izod impact values.

The best results of forging depend on the adoption of correct forging temperatures—the temperature should be high enough to give the steel the necessary plasticity, and not high enough to cause internal damage to the steel by overheating, which tends to cause intercrystalline weakness. The finish of the forging operation should be at the lowest temperature at which deformation can be reasonably produced, (unless the process is only a preliminary one). Adequate tools and power should be provided so that the work can proceed at a reasonable speed. The method of deformation should be such that the inside of the steel is worked as well as the outside. Many practical aspects of forging might be discussed, but space and time do not permit.

Reverting to the quantitative understanding of reheating problems, whether associated with reheating for hot working, hardening, normalizing, annealing, or tempering, it is necessary to have adequate data, particularly concerning thermal conductivity and specific heat. A short review of knowledge extant upon these values, may be of interest and is, therefore, included.

The Thermal Conductivity of Steels. Influence of Composition and Temperature.

The accurate determination of the thermal conductivity of

⁸³Aitchison, *Journal, Iron and Steel Institute*, 1925.

materials is rendered exceedingly difficult, chiefly on account of the lateral loss of heat by radiation. Many methods have been tried to take account of this loss, but considerable diversity exists in the results obtained. Before reviewing the effects of composition and temperature, therefore, it will be as well to note the varying values quoted for the thermal conductivity of pure iron.

Kohlrausch⁸⁴ gives 0.152 for wrought iron; Hobborn and Wien⁸⁵ give 0.156 for iron; Jaeger and Dieselhorst⁸⁶ give for pure iron, 0.161 at 18 degrees Cent. and 0.151 at 100 degrees Cent., and for wrought iron, 0.144 and 0.143 respectively; Hall⁸⁷ gives 0.1541; Hall,⁸⁸ correcting Angstrom's results, gives 0.1655; Simidu⁸⁹ extrapolating from the results of a series of carbon steels, obtained 0.1335, 0.1217 and 0.1284 for pure iron in the as-forged, annealed and quenched conditions respectively. Later,⁹⁰ he gives 0.134 for Swedish iron; Masumoto,⁹¹ using the same apparatus as Simidu, but a different series of steels, obtained by extrapolation, 0.1741. The observed value for a steel containing 0.1 per cent carbon and 0.38 per cent manganese, was 0.1447; Edser, in his book on "Heat", gives 0.166 at 0 degrees Cent. and 0.163 at 100 degrees Cent.; Benedicks, Backstrom and Sederholm⁹² deduce from observations on carbon steels, the value of 0.227 calories for pure iron. On a sample of iron containing 0.08 per cent carbon, 0.05 per cent silicon, 0.13 per cent manganese, the observed value was 0.187. Ingersoll and co-workers⁹³ give 0.1428 for electrolytic iron melted in vacuo; Sedstrom,⁹⁴ on a pure electrolytic iron, gives 0.18.

It is difficult to account for the great variations in the values quoted above. In some cases (especially the earlier ones) the analysis of the material is doubtful. However, neglecting these

⁸⁴Kohlrausch, *Annales de Physique et Chimie*, No. 4, 1888.

⁸⁵Hobborn and Wien, *Zeitschrift des Vereins deutscher Ingenieure*, Vol. 40, p. 45.

⁸⁶Jaeger and Dieselhorst, *Abh. Phys. Tech. Reich*, Vol. III, 1900, p. 269.

⁸⁷Hall, *Physical Review* of the American Physical Society, May and June, 1900, p. 277.

⁸⁸Hall, loc. cit.

⁸⁹Simidu, Science Reports of Tohoku Imperial University, Vol. 6, No. 3, September, 1917.

⁹⁰Simidu, Science Reports of Tohoku Imperial University, Vol. 4, No. 3, November, 1917.

⁹¹Masumoto, Science Reports Tohoku Imperial University, Vol. 16, No. 4, May, 1927.

⁹²Benedicks, Backstrom and Sederholm, *Journal*, Iron and Steel Institute, August, 1926.

⁹³Ingersoll, *Physical Review* of the American Physical Society, August, 1920, p. 126.

⁹⁴Sedstrom, *Inang. Diss.*, Stockholm, 1924.

and also those values deduced by extrapolation, we have a variation from 0.143 to 0.187. Some of the differences might be due to different temperatures of test or temperature ranges used for the test. Ingersoll used a method in which lagging merely was used to prevent radiation loss, and his results may be somewhat low. We are inclined to believe that the results of Benedicks and Sedstrom are somewhat too high, and on the whole we think the correct value for the thermal conductivity of pure iron at 20 degrees Cent. is between 0.16 and 0.17 c. g. s. units, and would take provisionally the value 0.165. This is very close to the value given in Edser's "Heat" and agrees with Hall's corrected values of Angstrom's results. While we think the Japanese method of measuring the conductivity is an excellent one and are inclined to place reliance on the individual determinations, we do not think that much importance should be placed on their extrapolated values for pure iron, since these were deduced by the method of least squares on so very few samples. The danger of this is revealed by the different results obtained by Simidu and Masumoto, who both used the same apparatus but a different series of steels. The value for pure iron deduced from both Simidu's and Masumoto's results would not be far removed from the value 0.165 we have decided upon.

Influence of Composition on Thermal Conductivity of Steels

Owing to the difficulty of measurement, the influence of composition has only been determined in a few cases. The influence of carbon has been determined by Simidu, Masumoto, Benedicks, Campbell and Dowd.⁹⁵ Campbell and Dowd did not make absolute determinations. Barrett, Brown and Hadfield⁹⁶ have also made relative determinations of a large number of steels, but the analyses given are incomplete so that allowances for other elements that might be present, cannot be made.

In dealing with influence of composition, it is perhaps best to consider the reciprocal of the conductivity, namely, the thermal resistivity rather than the conductivity itself, since it leads to more of a straight line relationship.

If the results of the foregoing observers are plotted, allow-

⁹⁵Campbell and Dowd, *Journal*, Iron and Steel Institute, Vol. II, 1917, p. 251.

⁹⁶Barrett, Brown and Hadfield, Royal Dublin Society, Vol. VIII, 2nd Series, 1904.

ances being made for the silicon and manganese contents, (assuming that 1 per cent manganese increases the thermal resistivity by 2 units and that 1 per cent of silicon increases it by 4 units), Masumoto's results plot very well on a straight line up to about 3 per cent of carbon, when the line curves upwards somewhat. The initial slope of the line indicates that 1 per cent of carbon, when not in solution, increases the thermal resistivity by 2.5 units. Simidu's values are somewhat higher than Masumoto's and are irregular, but the general trend is a slope of the same magnitude. Campbell and Dowd's results agree fairly well with Masumoto's as regards the influence of carbon. Benedick's results are irregular. As regards the influence of carbon in quenched steels, the data available are not sufficient to form a definite opinion, but the indications are, that up to 0.9 per cent carbon, the rate of increase of resistivity with carbon content, is about 7 units per 1 per cent of carbon in the form of martensite.

The influence of manganese has been determined by Matsushita⁹⁷ and by Sedstrom.⁹⁸ The latter found that 1 atom per cent of manganese increased the thermal resistivity by 1.9 units, or about 1.95 units per 1 per cent of added manganese. Matsushita's steels all contained 0.2 per cent of carbon, the amount of other elements not being stated.

The direct determination of the effect of silicon appears to have been done only by Sedstrom, who found 1 atom per cent silicon increased the resistivity by 3.24 units, i.e., the 1 per cent silicon increased the resistivity by 6.48 units. Masumoto, from his results on carbon steels, gives 5.087 as the effect of 1 per cent silicon. Campbell and Dowd found that a steel containing 0.104 per cent carbon, 0.122 per cent manganese, and 3.649 per cent silicon, had 3.17 times the thermal resistivity of a relatively pure iron when in the annealed condition, and 3.93 times when hardened. Assuming the value of 6.05 for pure iron, his standard would have a thermal resistivity of 6.08. This gives for the thermal resistivity of his silicon steel, values of 19.3 and 21.7 respectively. These figures, allowing for the carbon and manganese contents, indicate that 1 per cent silicon increases the resistivity between 3.5 and 4 units.

⁹⁷Matsushita, Science Reports of Tohoku Imperial University, No. 8, 1919, p. 79.

⁹⁸Sedstrom. loc. cit.

Nickel has been investigated by Ingersoll and his co-workers. The curve shows a sharp maximum at about 33 per cent nickel. The initial slope of the curve indicates that when in small amounts, 1 per cent nickel increases the resistivity by about 0.8 units. Sedstrom indicates that 1 per cent nickel increases the resistivity by 1.2 units.

Cobalt was studied by Honda⁹⁹ who found two maxima in the thermal resistivity concentration curve, occurring at about 9 and 91 per cent cobalt respectively, and a minimum at about 60 per cent cobalt corresponding to the formula FeCo_2 . The initial slope indicates that up to 5 per cent cobalt, 1 per cent of this element increases the thermal resistivity by 0.26 units.

The influence of tungsten has been studied by Honda and Matsushita, who investigated two series of tungsten steels containing 0.3 per cent and 0.6 per cent carbon respectively. The initial portions of the curves are irregular and one cannot deduce the influence of small amounts of this element.

Matsushita¹⁰⁰ investigated a series of chromium steels containing 0.6 per cent carbon. Some doubt must be placed on these results, however, since the difference between the results obtained on the quenched and annealed samples containing no chromium, are not consistent with the presence of 0.6 per cent carbon.

Influence of Temperature on the Thermal Conductivity of Steels

Hall,¹⁰¹ criticizing the various methods of measuring thermal conductivity, eulogizes Lorenz's method as particularly suited to studying the variation with temperature, and thinks that Lorenz's result is reliable. This gives the coefficient of variation with temperature as -0.0002282 per degree Cent. Hall, using Berget's method, obtained on pure iron $K = 0.1541$ ($1 - 0.0003t$) and for cast iron, $K = 0.1512$ ($1 - 0.00075t$). Jaeger and Dieselhorst¹⁰² give $K = 0.161$ at 18 degrees Cent. for pure iron and 0.151 at 100 degrees Cent., the corresponding values for wrought iron being 0.144 and 0.143. Callendar, for a cast iron (2 per cent carbon, 3

⁹⁹Kotaro Honda, Science Reports of Tohoku Imperial University, No. 8, 1919, p. 51.

¹⁰⁰Matsushita, Science Reports of Tohoku Imperial University, Vol. IX, No. 3, June, 1920.

¹⁰¹Hall, *Physical Review of the American Physical Society*, Vol. X, 1900, p. 277.

¹⁰²Jaeger and Dieselhorst, loc. cit.

per cent silicon, 1 per cent manganese) gives 0.114 at 54 degrees Cent. and 0.111 at 102 degrees Cent. Jaeger and Dieselhorst, for a 1 per cent carbon steel, give 0.108 at 18 degrees Cent. and 0.107 at 100 degrees Cent. Lees found a slight increase in the thermal conductivity of steel, from -180 to $+18$ degrees Cent. (from 0.113 to 0.115). Apart from these isolated attempts, the only real attempt to study the influence of temperature on the thermal conductivity of steels, is that by Honda and Simidu.¹⁰³ These authors measured the thermal conductivities of a series of carbon steels at temperatures up to 1650 degrees Fahr. (900 degrees Cent.). They found that the conductivity of a Swedish iron falls fairly rapidly with increase of temperature, from 0.134 at 30 degrees Cent. to 0.085 at 1145 degrees Fahr. (620 degrees Cent.). After passing the critical range, the conductivity remained fairly constant at 0.077.

The initial rate of fall (up to 100 degrees Cent.) indicates a coefficient of -0.0003 per degree Cent. in agreement with that of Lorenz. This coefficient is considerably reduced with increasing alloying content. With more than 0.44 per cent carbon, the thermal conductivity remains tolerably constant up to about 570 degrees Fahr. (300 degrees Cent.) when it begins to fall until the critical range is reached. Beyond the critical range, a slight rise of conductivity with temperature is indicated. It is clear that much more work is needed in this field.

Specific Heat of Steels as Affected by Temperature and Composition

For problems concerning the flow of heat, it is usual, in order to simplify the calculations, to assume a constant value of the specific heat over the whole range of temperatures concerned. It will be seen, however, from the following review of work on the subject, that this constancy is far from being realized, even in the case of pure iron between 0 and 2730 degrees Fahr. (1500 degrees Cent.). Further, although the influence of added elements has been studied in a few cases at temperatures not far removed from normal, only in the case of carbon has the influence been studied up to temperatures in the neighborhood of 1590 degrees

¹⁰³Kotaro Honda and Simidu, Science Reports of Tohoku Imperial University, Vol. VI, No. 4, November, 1917, p. 219.

Fahr. (1200 degrees Cent.). From these results it is evident that it would be unwise to infer that the variations in specific heat, at ordinary temperatures, produced by the addition of a certain element, would be the same at elevated temperatures. However, it is as well to review the work which has been done in this direction.

Specific Heat of Pure Iron

Of the numerous attempts made to determine the specific heat of pure iron, fair agreement has been reached for the value of this constant in the range 0 to 100 degrees Cent. The following is a list of most of the determinations:—

Umino ¹⁰⁴	$S_0^{100} = 0.1102$
Oberhoffer and Grosse ¹⁰⁵	$S_0^{100} = 0.1107$
Oberhoffer ¹⁰⁶ $S_0^{250} = 0.117$,	S_0^{100} (extrapolated) = 0.1105
Honda ¹⁰⁷	$S_{20}^{150} = 0.1126$
Harker ¹⁰⁸ $S_0^{200} = 0.1175$ =	S_0^{100} (extrapolated) = 0.1117
Wust, Meuthen and Durrer ¹⁰⁹	$S_0^{100} = 0.1111$
Nacciau ¹¹⁰	$S_0^{100} = 0.1117$
Bystrom ^x	$S_0^{100} = 0.1126$
Nichol ^x	$S_{15}^{100} = 0.1152$
Tomlinson ^x	$S_0^{100} = 0.1130$
Lorenz ^x	$S_0^{100} = 0.1107$

The more recent of these results are all not far removed from 0.111 units: as for the variation of specific heat with temperature, however, agreement is not so good. They all agree, however, that the specific heat increases with temperature, rising very rapidly just below the magnetic change point. The specific heat is maintained constant throughout the gamma region, at a value between 0.145 and 0.166 units. Some investigators report that the specific heat in the delta region returns to the value which it had in the alpha region above the magnetic change point.

^xBystrom, Nichol, Tomlinson and Lorenz taken from Physico Chemical Tables, Castell-Evans, Griffins, 1902.

¹⁰⁴Umino, Science Reports of Tohoku Imperial University, No. 5, 1926, p. 597, and No. 3, 1926, p. 332.

¹⁰⁵Oberhoffer and Grosse, *Stahl und Eisen*, Vol. 47, April 7, 1927, p. 576.

¹⁰⁶Oberhoffer, *Stahl und Eisen*, Vol. 27, 1907, p. 1764.

¹⁰⁷Kotaro Honda, *Japanese Journal of Physics*, Vol. 1, No. 7, 8, 1922, p. 71.

¹⁰⁸Harker, *Proceedings*, Physical Society of London, 19, 1905.

¹⁰⁹Wust, Meuthen and Durrer, *Stahl und Eisen*, Vol. 38, 1918, p. 177.

¹¹⁰Nacciau, *Atti. R. A. de Torino*, Vol. 23, 1889, Beiblätter, Vol. XII, 1888, p. 326.

Effect of Composition

As regards the influence of carbon, Honda¹¹¹ gives the mean specific heat between 20 and 150 degrees Cent. of a series of carbon steels, and his results plot fairly well on a straight line, which indicates that for this range of temperature, 1 per cent carbon in annealed steels, increases the specific heat by 0.0058 units. Umino¹¹² has also determined the specific heat of a series of carbon steels in the whole range up to 2280 degrees Fahr. (1250 degrees Cent.). His results, while slightly below those of Honda, indicate approximately the same influence of 1 per cent carbon (actually 0.0052 units). Brown¹¹³ has determined the specific heat of a number of steels. His specimens were all water quenched from a cherry red heat and presumably, therefore, in some cases, were in the hardened condition. This may account for his values for the higher carbon content, being somewhat greater than those of Honda and Simidu. Umino showed that anomalous changes took place in the region of the allotropic changes. He also showed that the increase in specific heat with carbon content is not maintained at the higher temperatures, and that in the gamma region, high carbon content causes a considerable fall in the specific heat.

As regards the influence of manganese, from Brown's results it would appear that 1 per cent manganese in small amounts, increases the specific heat (0 to 100 degrees Cent.) by 0.0006 units.

As regards the influence of silicon, we have only Brown's results to guide us. He deduces that 1 per cent silicon in amounts up to 2 per cent increases the specific heat by 0.003 units: above this amount it has no effect. However, from both Honda's and Umino's results on carbon steels which contained varying amounts of silicon in small amounts, it would appear that the influence of silicon up to 2 per cent is not so great as Brown indicates. Oberhoeffler and Gross report that a transformer iron containing 4 per cent silicon, has lower specific heat in the range 0 to 100 degrees Cent. than pure iron, having a value of 0.1080 compared with 0.1107 for pure iron. They state further that in the range above the magnetic change point (there is no gamma range) the true specific heat is constant at 0.18475, compared with 0.165 in the

¹¹¹Kotaro Honda, loc. cit.

¹¹²Umino, loc. cit.

¹¹³Brown, *Transactions*, Royal Dublin Society, Vol. IX, Series II, 1905-1909, p. 59.

case of pure iron in the alpha and delta ranges above the magnetic change point.

The influence of nickel on the specific heat of steels has been studied by Ingersoll and his co-workers¹¹⁴ and by Kawakami.¹¹⁵ Both investigators reveal a maximum in the specific heat at 35 per cent nickel corresponding with the composition of Invar. Kawakami reports a minimum at 85 per cent nickel where Ingersoll finds none. There are wide differences in the actual values of specific heat quoted by the two observers.

With regard to the influence of other elements, excepting that of Brown, no other work on the influence of elements other than those already mentioned appears to have been published. The following are Brown's conclusions:—1 per cent tungsten increases the specific heat of iron by 0.0028 units, when in amounts below 1 per cent. With 3.5 per cent tungsten, the specific heat falls to that of pure iron, and a further addition of 12 per cent of this element decreases the specific heat by 0.0093 units. 1 per cent aluminum has no influence on the specific heat of iron. Chromium, copper and cobalt have no effect on the specific heat of iron when large amounts of carbon are present.

SECTION IV

SPECIAL STEELS

It was due essentially to the development of armaments in the pre-war decades that the metallurgy of the special steels evolved so rapidly. It might conversely be put that the metallurgical advances in themselves made possible the form and magnitude of warfare typical of the World War. The modern battleship, destroyer, submarine, airplane and the armored tank, together with their armaments, were impossible but for the collaboration of the engineer and the metallurgist. Posterity alone can give judgment as to the "merit" of making possible the conditions under which the war was fought. In any case, the last few decades have shown that a valuable "special steel" metallurgy has been created which will serve equally the arts of peace

¹¹⁴Ingersoll, *Physical Review of the American Physical Society*, August, 1920, p. 126.

¹¹⁵Kawakami, *Science Reports of Tohoku Imperial University*, Vol. XV, Series I, No. 2, May, 1926, p. 251.

as those of war, and it is essentially from that point of view that this matter should be considered. The great services of power generation; transit by land, sea or air; the production and preparation of food; not to mention the multitude of services available through the utilization of mechanical devices based upon steel. In all these fields of activity, efficiency can be materially increased by making use of the valuable characteristics of the special steels, which, except in limited circles, are, as yet, insufficiently known.

One must look in vain for records concerning the ballistic qualities of the gorgeous suits of armor produced by our forebears. Romantic literature contains indications of somewhat sudden achievements, as when Robin Hood cursed "that coat of Spanish mail." If, instead of Spanish mail, the arrow shot by our Greenwood friend had simply needed to pass through "honest English armor," a second shot would have been unnecessary! Does this indicate a passing from iron to hardened and tempered steel? The early understanding of the production of steel by the carburization of iron soon led to a mastery of the art of hardening and tempering, as is perhaps best exemplified in some of the excellent early swords, which may still be studied, produced by famous sword makers. Such carbon steel may be so hardened and tempered that it is either hard and brittle, or hard and tough, and practical experiment no doubt led to an empirical understanding of the treatment processes sufficiently reliable to give world fame to the most successful exponents of the art at a time when the world was literally ruled by the sword. The steel available, however, was only carbon steel, it did not even contain any quantity of manganese, and could not be hardened unless the form in which it was treated was small, as in the case of a knife or a sword. The exquisite temper required could only be obtained if adequate hardening preceded the necessary careful tempering. Until the discovery of the crucible process by Huntsman in the early part of the eighteenth century, carbon was mainly introduced into iron by the cementation process, i.e., by exposing the bars of iron, packed in charcoal, to a high temperature for a considerable time. The bars of carburized iron so produced were hammered to the form required. It will be seen, therefore, that until comparatively recent time, steel was only available in too

small a quantity to permit of the development of the present mechanical age.

It was the introduction of Bessemer's process, followed rapidly by that of the Siemens-Martin open-hearth, which permitted engineers to envisage the use of the present tremendous tonnage of steel. These processes made possible not only a great tonnage of steel, but also ingots of considerable size, thus making possible the production of important large forgings for engineering purposes. The crucible process was still retained for the manufacture of tool steels, and, indeed, is still used for the highest qualities; the new processes were developed for the production of low carbon steel for ship plates, sheets and structural steel; while from steel containing a medium carbon content, the necessary rails and tires for the great railway expansion were produced. As time passed, very large ingots came to be made, but still of carbon steel, and owing to the need for toughness, the carbon content was kept low. It was only in the last decades of the nineteenth century that the influence of alloying nickel, chromium and other special elements became known and practiced. Indeed, it can be said that until the beginning of the present century, comparatively little use was made of the accumulating knowledge of special steels. The development of the motor car, and of the airplane engine, covers the period of the rapid extension of the use of such steels, and, indeed, many of the parts even of the mass production cars in America and Europe will be found to consist of excellently heat treated alloy steel of high mechanical characteristics.

As will be discussed later, the plain carbon steels, owing to the fact that when the masses became large they could not be adequately heat treated, are generally used in the rolled or normalized condition, and, therefore, consist structurally of the two constituents pearlite and ferrite. In very mild low carbon steels, they consist of ferrite, i.e., pure iron crystals, with areas of the strong duplex constituent pearlite sparsely distributed throughout the mass. In Table VI will be found the results of attempts made¹¹⁶ to abuse this type of steel, and it will be observed how "fool-proof" it really is. With higher carbon content, the relative proportion of pearlite to ferrite increases, thus resulting in the increase in hardness and strength. With higher carbon content,

¹¹⁶Hatfield and Duncan, N. E. Coast Institute of Engineers and Shipbuilders, March 19, 1920.

the steel becomes more susceptible to wrong time-temperature treatment.

The point which it is desired to make is that whether one is considering locomotive crank axles, or marine shafting, one should look upon the metal, not as "steel," but rather as a conglomerate of ferrite crystals and pearlite. It is to the presence of the relatively large ferrite crystals that one must look for the explanation of the low fatigue values possessed by carbon steels when compared with the special alloy steels. When the mechanical characteristics of steels are carefully considered, it will be agreed that frequently the essentially determining value, from the designer's point of view, is the fatigue strength. A part must for its life successfully resist a repeated stress, or a reversal of stress of a certain magnitude, and the higher the strength of the material in that respect, and the greater the reliance which can be placed upon its homogeneity, the higher will be the efficiency of the designer's productions. The work of Gough, Haigh and Lea in England, Moore and Kommers in America and others, has, during the last decade or two, done much to increase our knowledge concerning the response of steel to conditions where failure from fatigue must be safeguarded. This is beautifully illustrated in some of the parts of a modern airplane engine, where hardened and tempered alloy steels of very high fatigue values, produced under the best technical conditions, are used, and factors of safety are employed, which would not be even considered under many of the extremely empirical conditions where the engineer is responsible for more massive machinery produced from the low carbon steels usually employed. It is sometimes not appreciated that the crankshaft of a good motor car, for instance, in its "useful" life may be submitted to 200,000,000 reversals of stress. A propeller shaft of a large ocean liner in recent years, made of mild carbon steel, smashed in service after approximately 677,000,000 reversals of stress over nineteen years, the fracture, it is understood, showed no "defect."

The hardness and tensile strength are increased in simple carbon steel by increasing the carbon content, but, whilst the fatigue strength is increased, it increases disproportionately to the other values just stated, and, at the same time, the ductility or capacity for plastic deformation rapidly decreases. Reference to

Table VII
Carbon Steels

	0.15% Carbon Steel	30-ton Carbon Steel	40-ton Carbon Steel	50-ton Carbon Steel	0.9-1.0% Carbon Steel
<i>Analysis</i>					
Carbon, per cent	0.15	0.31	0.45	0.60	0.90
Manganese, per cent	0.30	0.67	0.70	0.69	0.55
Silicon, per cent	0.06	0.14	0.15	0.20	0.11
Sulphur, per cent	0.034	0.048	0.044	0.04	0.036
Phosphorus, per cent	0.013	0.04	0.036	0.039	0.031
Chromium, per cent	nil	nil	nil	nil	nil
Nickel, per cent	nil	nil	nil	nil	nil
Condition	Normalized 900° C. (1651° F.)	Normalized 850° C. (1562° F.)	Normalized 820° C. (1508° F.)	Normalized 810° C. (1490° F.)	Normalized 850° C. (1562° F.)
<i>Tensile</i>					
Elastic limit, lbs./sq. in.	31,400	44,900	48,200	60,500	51,900
Elastic limit, tons/sq. in.	14.0	20.05	21.5	27.0	23.16
Yield point, lbs./sq. in.	31,400	46,400	51,300	65,300	72,600
Yield point, tons/sq. in.	14.0	20.70	22.9	29.16	32.4
Max. stress, lbs./sq. in.	47,900	78,800	92,300	108,900	133,100
Max. stress, tons/sq. in.	21.4	35.17	41.2	48.60	59.4
Elongation, per cent	45.0	30.5	25.0	22.0	11.0
Reduction of area, per cent	73.56	54.6	47.0	37.9	15.5
<i>Torsion</i>					
Yield, lbs./sq. in.	17,100	31,600	34,900	37,100	42,100
Yield, tons/sq. in.	7.63	14.1	15.6	16.6	18.8
Prob. max. stress, lbs./sq. in.	46,900	61,600	65,000	74,600	80,000
Prob. max. stress, tons/sq. in.	20.95	27.51	29.0	33.3	35.7
Degrees twist	1,070	548	434	320	184
Izod, foot-pounds	81	33	23	8	2
Arnold, reversals	456	444	500	480	352
Stanton, blows	1,016	1,413	1,244	1,139	264
Sankey, foot-pounds	2,300	1,700	3,974	2,496	1,112
Brinell Hardness Numbers	95	156	170	223	286
Shore Hardness Numbers	21	27	29	35	40
Fatigue range, lbs./sq. in.	±26,200	±28,700	±34,700	±40,300	±37,000
Fatigue range, tons/sq. in.	±11.7	±12.8	±15.5	±18.0	±16.5

Table VII will enable a quantitative consideration of this effect of increasing the carbon content.

Such is the result of so modifying the balance of the ferrite crystals and pearlite in the conglomerate of which the steels consist. In mass of any magnitude, the great advantages of heat treatment cannot be obtained with carbon steels. For the hardening of a steel, a temperature must be attained at which it consists of a homogeneous solid solution, and then cooling must be so rapid as to prevent the transformation to the normal constituents taking place. In carbon steel, such rapid cooling is necessary that only in the thinnest sections is it practicable to obtain the hardened condition. The addition of nickel, chromium and other selected elements results in the transformation from the solid solution state being so slowed down that the metallurgist may, with

discriminating exactitude, advise modifications of analysis suitable for the successful hardening of even extremely large masses. Once the mass is hardened, it may be tempered to give, in its final condition, greatly enhanced mechanical values. Hardness and high tensile strengths are obtained with proportionally much higher fatigue strengths, and with incidentally much greater capacity for plastic deformation than in the case of carbon steels of similar mass.

In the first place, it is necessary to record that the addition of manganese in quantities varying from 1.6 to 0.4 per cent, in the Bessemer and open-hearth processes, really constituted the first development in "alloy" steel production. Apart from the strictly metallurgical values of this manganese content for deoxidation purposes, it was found that with manganese present, steel of the same carbon content had materially greater strength, the pearlite occupying a greater volume than in steel not containing the manganese; practice subsequently in later years stabilized the manganese content in these steels with fairly narrow limits; hence, the fact of its presence being a constant, its influence became taken for granted. Generally speaking, ordinary Siemens-Martin open-hearth acid steel contains 0.5 to 0.7 per cent, Siemens-Martin open-hearth basic steel contains 0.3 to 0.5 per cent, whilst the Bessemer steels generally run 0.8 to 1.0 per cent.

Strictly speaking, however, there are sufficiently numerous exceptions for more interest to be taken in the influence of the element on the properties of the steel.

The influence of manganese being confirmed, it is not surprising that the next element to be alloyed with the steel, in quantity, was nickel, and it was soon found that 2.0 to 3.0 per cent of this element resulted in still further enhanced mechanical properties for similar reasons as in the case of the manganese.

We now come to the practice of hardening and tempering alloy steels. It was found that with the manganese and nickel present, even oil-quenching resulted in reasonably effective hardening of fairly heavy sections, and it was found that such steel subsequently tempered was of excellent properties. The addition of chromium along with nickel still further improved the possibilities of treatment, and thus arose the nickel-chromium steels. Subsequent experiments justified adding to these already complex

Table VIII

Steel	Analysis							Heat Treatment	Tensile			Reduction of Area, per cent	Elongation, per cent	Izod foot-pounds	Britnell	Fatigue Range, lbs. per sq. in.
	C	Mn	Si	Ni	Cr	V	Mo		Yield Point, lbs. per sq. in.	Max. Stress, lbs. per sq. in.						
1. Manganese	0.37	1.80	0.15	0.11	...	...	...	O. H. 1562° Fahr. T. 1166° Fahr., A. C.	77,500	106,800		62.6	27.0	21	217	45,900 20.5
2. Nickel	0.35	0.60	0.30	3.00	...	...	...	O. Q. 1562° Fahr. T. 1166° Fahr., W. Q.	90,700	110,900		63.5	23.5	70	228	48,200 21.5
3. 1 per cent Chromium	0.46	0.72	0.21	0.2	1.06	...	...	O. H. 1562° Fahr. T. 1112° Fahr., O. Q.	120,500	138,400		60.4	21.0	45	286	62,700 28.0
4. Nickel-chromium	0.31	0.55	0.12	3.3	0.75	...	...	O. Q. 1526° Fahr. T. 1112° Fahr., O. Q.	121,000	136,600		62.0	21.0	49	285	62,700 28.0
5. Chromium-vanadium	0.46	0.64	0.19	0.19	1.48	0.33	...	O. H. 1562° Fahr. T. 914° Fahr.	190,400	199,400		46.0	16.0	16	410	78,400 35.0
6. Air-hardening, nickel-chromium-	0.28	0.45	0.23	4.32	1.41	...	...	A. H. 1490° Fahr.	233,000	248,600		41.8	13.0	30	477	91,800 41.0
7. Nickel-chromium- vanadium	0.24	0.53	0.23	3.09	1.24	0.17	...	O. H. 1562° Fahr. T. 1148° Fahr., 1/2 hr.	139,800	143,800		66.8	21.0	80	302	65,000 29.0
8. Nickel-chromium	0.30	0.62	0.21	2.87	0.55	...	0.64	O. H. 1562° Fahr. T. 1157° Fahr., A. C.	131,700	143,400		55.0	19.0	30	293	65,000 29.0
9. Chromium-silicon	0.48	0.34	1.0	0.10	0.74	...	...	O. H. 1562° Fahr. T. 896° Fahr.	195,600	210,800		7.0	7.0	8	425	80,600 36.0
10. Silico-manganese	0.57	1.0	2.03	...	...	...	...	O. H. 1607° Fahr. T. 896° Fahr.	188,200	204,300		9.5	24.5	14	416	80,600 36.0

steels the elements vanadium, molybdenum and, occasionally, tungsten. Concurrently valuable steels were developed by the simple addition of chromium, or chromium plus a little vanadium. Increasing the manganese to 1.5 to 2.0 per cent was found, in some cases, advantageous; while the addition of substantial quantities of silicon, along with such manganese contents, or silicon with small quantities of chromium, also provided useful steels. Thus the following classes of steels require considering:—

Manganese steels
Nickel steels
Chromium steels
Nickel-chromium steels
Chromium-vanadium steels
Nickel-chromium molybdenum steels
Nickel-chromium-vanadium steels
Nickel-chromium-tungsten steels
Chromium-silicon steels
Manganese-silicon steels

All these steels come in the class which the lecturer proposes to discuss as ordinary alloy steels, since the simple object in view, in each case, is to facilitate the production of excellent mechanical characteristics, as a result of heat treatment. In Table VIII will be found an indication of the characteristics of such hardened and tempered steels.

There is another class of steels of great importance, in which, by the addition usually of much greater quantities of the alloying elements, other valuable characteristics than merely improved mechanical strength, in the ordinary sense, are conferred upon the material. This class the lecturer proposes to designate the Special Alloy Steels. For instance, by adding 14 per cent manganese, unique wearing and nonmagnetic properties may be obtained; by adding 12 to 14 per cent chromium, stainless and nonrusting steel, as used for cutlery, is produced; while acid-resisting steels result from the further increase of the chromium, along with a suitable nickel content. By adding 5 to 6 per cent tungsten, permanent magnet steel is produced; while the addition of chromium or cobalt still further enhances the coercive force obtainable after treatment. Steels of high magnetic permeability are achieved by adding silicon or aluminum. An exceptionally low coefficient of expansion can be obtained by alloying a high percentage of nickel. Heat-resisting steels of great value are produced by the alloying,

in considerable quantities, of chromium and silicon; chromium, nickel and tungsten; or chromium, nickel and silicon. Lastly, one might mention the high speed tool steels, where tungsten, chromium, molybdenum, vanadium and cobalt are alloyed in varying proportions, with invaluable results as regards cutting characteristics. It will thus be seen that the following important classes of steels are each worthy of careful study:—

Wear-Resisting steels	
Stainless and Rust-Resisting steels	(See Section V)
Acid-Resisting Steels	(See Section V)
Heat-Resisting steels	(See Section VI)
Magnet steels	
Permeability of steels	
Nonmagnetic steels	
Steels of Low Coefficient of Expansion	
Steels of High Electrical Resistance	
Tool Steels	(See Section VII)

Wear-Resisting Steels

When problems of wear have to be dealt with, a reasonable solution is generally found either by the employment of:—

- (a) 14 per cent manganese steel
- (b) Air-hardening nickel-chromium steel
- (c) High carbon-chromium steel
- (d) Case-hardening steels
- (e) Steel capable of nitrogenization

As regards 14 per cent manganese steel, which might be considered to be the original alloy steel, and for which we are indebted to Sir Robert Hadfield, the literature on the subject contains adequate information. The steel contains 11 to 14 per cent manganese, with 1.0 to 1.5 per cent carbon, and is in its best condition for resisting certain types of wear when it has been toughened by quenching from a temperature of approximately 1830 to 1920 degrees Fahr. (1000 to 1050 degrees Cent.). The steel is extremely interesting as being austenitic and practically nonmagnetic. It has the capacity for rapidly work hardening, which makes this steel particularly valuable. Its one disadvantage, however, is that it tends to deform under heavy loads, and hence, although its sphere of utility is large, there are definite limitations to its application. For dredger buckets, stone breaking machinery and similar allied applications, the material is eminently satisfactory.

The air-hardening nickel-chromium steel has proved invaluable for numerous small highly finished wearing parts, particularly for gears. The analysis generally employed is as follows:—

	Per Cent	
Carbon	0.25	to 0.32
Silicon	0.30	max.
Manganese	0.35	to 0.60
Sulphur	0.035	max.
Phosphorus	0.035	max.
Nickel	4.0	to 4.5
Chromium	1.00	to 1.50

After hardening by air-cooling from a temperature of 1470 to 1508 degrees Fahr. (800 to 820 degrees Cent.), followed by tempering at about 480 degrees Fahr. (250 degrees Cent.) with a view to reducing the residue of internal stress, test values of the following order are obtained:—

Yield Point, pounds per square inch	190,400 to 224,000
Maximum Stress, pounds per square inch	224,000 to 291,200
Elongation, per cent	16.0 to 8.0
Reduction of Area, per cent	20.0
Izod Impact, foot-pounds	20 to 10

The carbon-chromium steels are manufactured in large quantities in Europe, and are particularly used in connection with the ball and roller bearing industries, and also for die blocks. The following analysis may be taken as representative:—

	Per Cent	
Carbon	0.95	to 1.05
Silicon	0.15	to 3.0
Manganese	0.35	to 5.0
Chromium	1.3	to 1.6
Sulphur	0.04	max.
Phosphorus	0.04	max.
Nickel	0.25	max.

The material is hardened by quenching in water from 1500 to 1540 degrees Fahr. (820 to 840 degrees Cent.), and is used in this condition, when it has a Brinell hardness in excess of 650, and a very high Shore value. The author considers this an extremely successful steel.

Case-hardening steels have received so much attention that they need not be discussed at length. It is now definitely established, when considering case hardening steels, that a plain dead mild steel, i.e., the absence of special elements, when adequately

case hardened, gives the hardest surface of all. If the general structure of the part is put into a satisfactory condition by suitable refining prior to the hardening operation, it must be agreed that a very good article is produced. If a stronger core is required, it is customary to add to the steel either 3 or 5 per cent nickel, and, at times, chromium in addition to the nickel. There is, however, definite evidence that these alloy case-hardening steels, whilst having a core of much greater strength, do not possess quite so high a hardness value as regards the surface.

The process of nitrogenization is relatively new, and is the result of researches of Fry of Essen with subsequent developments in America and Europe. In this process a chromium steel containing about 1.0 per cent of aluminum with or without the addition of other elements is used, and the steel, after being put into its final heat treated condition, and machined to shape, is given a hardened surface by exposure to ammonia gas at a temperature of about 932 degrees Fahr. (500 degrees Cent.). An intensely hard thin surface hardening is obtained, and undoubtedly there is a future for the application in many useful directions of the use of this steel and this method of hardening. The steel and the process are, however, at the present time being developed, and it cannot be said that present procedure constitutes finality. It will be quite clear that a process of hardening which can be carried out at a black heat cannot but be invaluable, owing to the great lessening of the danger from distortion.

Magnet Steels

This subject was dealt with in a most interesting manner by J. A. Mathews. Apart from plain carbon steels, the following steels have been used for making permanent magnets:—

- (a) Tungsten magnet steels
- (b) Chromium magnet steels
- (c) Tungsten-chromium magnet steels
- (d) Cobalt magnet steels
- (e) Cobalt-chromium with similar steels containing essentially large amounts of cobalt.

(a) *Tungsten steels.* Of these, tungsten steels are the most common. They contain approximately 6 per cent tungsten and 0.6 to 0.75 per cent carbon. To obtain the best magnetic properties, they are quenched in water from 1562 degrees Fahr. (850 degrees

Cent.) and are used in this condition. The coercive force obtainable depends largely on the carbon content. A tungsten steel containing 0.6 per cent carbon should give a coercive force of 58; one containing 0.65 per cent carbon, 63; 0.70 per cent carbon, 68; and 0.75 per cent carbon, 72. The remanence in all cases is of the order of 10,000 to 11,000.

The figures quoted for the coercive force are the best one can expect from the given composition. It frequently happens, however, that these figures are not reached in practice, due to conditions under which the material has been prepared. It has been found that maintaining the material at temperatures between 1290 and 2190 degrees Fahr. (700 and 1200 degrees Cent.), has a deleterious effect on the subsequent magnetic properties. This effect, which has been given the name of "spoiling," occurs most rapidly at temperatures of about 1740 degrees Fahr. (950 degrees Cent.). It also takes place fairly rapidly at the hardening temperature, and the material, therefore, must not be held too long at this temperature before quenching. Reheating the spoiled material to 2282 degrees Fahr. (1250 degrees Cent.) followed by cooling in air, reconditions the material for the purpose of making permanent magnets. Care must also be taken in heating tungsten magnet steel, owing to the readiness with which it decarbonizes in an oxidizing atmosphere.

(b) *Chromium magnet steels.* A variety of compositions has been recommended by various investigators for magnet steels containing chromium. Adams and Goeckler¹¹⁷ recommend 1.1 per cent carbon and 4 per cent chromium as the optimum percentage composition. Oil-quenched from 1580 degrees Fahr. (860 degrees Cent.) this steel gives a coercive force of 70, with a remanence of 9,400. Gumlich¹¹⁸ recommends 6 per cent of chromium, which when oil-quenched from 1625 degrees Fahr. (885 degrees Cent.), gives coercive force 72 and remanence 9,600, and values not greatly superior to those with 4 per cent of chromium. We, ourselves, have, however, obtained good results with steels containing 1 per cent carbon and 1.4 per cent chromium, as the following data show.

¹¹⁷J. R. Adams and F. E. Goeckler, "Some Factors Affecting Coercive Force and Residual Induction of Some Magnet Steels, TRANSACTIONS, American Society for Steel Treating, Vol. X, No. 2, 1926, p. 173.

¹¹⁸Gumlich, *Zeitschrift für Physik*, Vol. 14, 1923, p. 241.

	Treatment Degrees-Degrees		Coercive force	
	Fahr.	Cent.	Remanence	
Water-Quenched	1580	860	65	9,000
Water-Quenched	1508	820	64½	9,850
Water-Quenched	1436	780	61	10,310

For the higher chromium steels, oil-quenching is recommended. This, in the majority of cases (depending on the cross section) gives higher values for the coercive force, but with somewhat reduced values of the remanence. Further, in oil-quenching, the material is not so prone to cracking. According to Evershed, chromium steels are even more conducive to spoiling than tungsten steels, but information on the spoiling effect and the proper recovery treatment for the former steels, does not appear to have been so thoroughly investigated as has been the case with tungsten steels.

(c) *Tungsten-chromium magnet steels.* The addition of 0.75 to 1 per cent chromium to ordinary 6 per cent tungsten magnet steels appears to increase the coercive force slightly without seriously affecting the remanence. Parkin¹¹⁹ used steels containing 0.73 to 0.80 per cent chromium with 6 per cent tungsten, and obtained the best results with 0.6 per cent carbon. He, however, submitted all his steels to a normalizing treatment of between 1510 and 1740 degrees Fahr. (820 and 950 degrees Cent.), and his results, therefore, are somewhat vitiated by the spoiling they so obtained. Evershed considers that the addition of chromium renders the material more liable to the effect of spoiling, and also renders the ultra-heated condition more persistent.

(d) and (e) *Cobalt magnet steels.* Cobalt magnet steel, discovered by Honda and Takagi, the Japanese workers, in 1917, consists essentially of 30 to 40 per cent cobalt with 0.4 to 0.8 per cent carbon. In their patent specifications, they, however, extend the cobalt content to 20 to 60 per cent, and also include 3 to 9 per cent of tungsten and 1.5 to 3 per cent of chromium. The material is best oil-quenched from 1740 to 1830 degrees Fahr. (950 to 1000 degrees Cent.), when it has a coercive force of 220 to 250, coupled with a remanence in the neighborhood of 10,000. On account of the high coercive force of this material, magnetization is difficult, and it is necessary to use very high magnetizing fields (1400 c.g.s. units) in order to get saturation and to yield the high figures of

¹¹⁹Parkin, *Journal*, Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. XIII, 1924.

remanence and coercive force quoted. With a magnetizing field of the order of 400 c.g.s. units, the remanence is of the order of 9,500 c.g.s. units, and the coercive force 180 to 220.

Since the discovery of the above cobalt magnet steels, steels containing varying amounts of cobalt with additions of other elements are being made.

Permeability of Steels

Our interest in this aspect of matters arises largely in connection with the manufacture of turbine forgings. Scientific and technical literature contains little data dealing with that field, although much has been published as regards the transformer end of the subject. Particularly useful is a summary of data extant to be found in *World Power* August, 1927.

The following is a statement of the magnetic results obtained in the Brown-Firth research laboratories on turbine forgings and similar articles, with a view to determining—(1) what magnetic properties might be expected on these articles, and (2) how the results are affected by composition and heat treatment.

Typical results are collected in Table IX. Samples in all cases were taken from the heat treated forging, machined down to $\frac{3}{8}$ inch diameter, and tested by a ballistic method in a ring yoke similar to that employed by the National Physical Laboratory. All measuring instruments were checked and calibrated by the National Physical Laboratory and the accuracy of the measurements was periodically checked by a standard bar, which had been submitted to the National Physical Laboratory for their magnetic measurements.

It is very difficult from these tests from finished forgings to correlate the magnetic results with either variations in composition or heat treatment. A general survey of the whole of the results, however, indicates that—

- (1) Increase of carbon tends to produce inferior results.
- (2) Small amounts of nickel up to 1 per cent are not detrimental from a magnetic point of view. In fact it tends to enhance the magnetic properties except in very low magnetic fields.
- (3) Nickel up to 4 per cent tends to enhance the magnetic properties in high fields, but there is a danger of getting poor results in low fields.

Table X
Tests on Heat Treated Bars ($\frac{3}{8}$ " Diameter) to Illustrate Effect of Heat Treatment and Composition

	Analyses				Cr	Treatment	Brinell	B Values for H =					
	C	Mn	Si	P				10	20	40	50	60	100
Plain Carbon Steels	0.41	0.50	0.11	0.06	0.045	920° C. $\frac{1}{2}$ hr. M. C.	174	7700	11250	13950	14650	15200	16550
						850° C. A. C.	207	8000	11000	14200	14900	15500	16950
	0.32	0.59	0.11	0.03	0.03	As forged	159	8600	12800	15250	15800	16250	17300
						850° C. $\frac{1}{2}$ hr. M. C.	141	9750	12600	14750	15350	15850	17050
1 $\frac{1}{4}$ % Nickel Steel						850° C. A. C.	160	6100	11250	14600	15350	15850	17250
	0.31	0.67	0.14	0.05	0.04	As forged	145	8300	11900	14150	14800	15300	17250
						850° C. $\frac{1}{2}$ hr. M. C.	152	10300	13100	15250	15750	16200	17350
						850° C. A. C.	163	8250	11150	14300	15600	16100	17450
3 % Ni-Cr Steels	0.28	0.28	0.13	0.06	0.03	As forged	182	6900	12700	15350	16450	16900	17950
						850° C. $\frac{1}{2}$ hr. M. C.	134	9700	13350	15450	16000	16400	17500
	0.22	0.32	0.13	0.04	0.03	As forged	174	8700	13300	15900	16500	16950	18000
						850° C. $\frac{1}{2}$ hr. M. C.	131	8700	13100	15300	15900	16250	17200
2 $\frac{1}{2}$ % Cobalt 1 % Manganese	0.40	0.57	0.26	0.04	0.02	As forged	200	6700	12050	15100	15750	16100	17300
						900° C. $\frac{1}{2}$ hr. M. C.	174	8400	12550	15000	15600	16100	17450
						As forged	240	2750	8100	12300	13300	14150	15600
	0.22	0.29	0.17	0.03	0.01	850° C. $\frac{1}{2}$ hr. M. C.	174	5100	10250	13950	14900	15600	17300
2 $\frac{1}{2}$ % Chromium 1 % Manganese plus 1 % Copper	0.18	0.49	0.16	0.03	0.01	900° C. A. C.	204	4200	9050	13200	14400	15200	17400
						850° C. $\frac{1}{2}$ hr. M. C.	200	3950	8900	12900	13800	14500	16300
	0.33	0.55	0.21	0.04	0.02	900° C. A. C.	254	1500	5150	9550	10650	11450	13750
						As forged	191	8300	12950	15200	15800	16250	17400
1 % Silicon	0.34	0.69	0.31	0.04	0.03	900° C. $\frac{1}{2}$ hr. M. C.	186	8000	12350	14900	15500	15950	17050
						As forged	200	6900	12500	15550	16200	16700	18050
						900° C. $\frac{1}{2}$ hr. M. C.	170	8100	12400	15000	15600	16100	17400
	0.30	1.28	0.29	0.04	0.03	As forged	205	3600	10650	14650	15500	16100	17450
1 % Chromium 1 % Manganese plus 1 % Copper						900° C. $\frac{1}{2}$ hr. M. C.	182	6050	10700	14200	15050	15600	16950
	0.36	0.79	1.27	0.04	0.03	As forged	222	4350	11300	14700	15500	16050	17350
						900° C. $\frac{1}{2}$ hr. M. C.	209	7000	10950	14300	15100	15600	16800
	0.35	0.91	0.28	0.03	0.03	As forged	200	1550	7550	12600	13700	14300	16000
1 % Nickel Steel	0.41	0.61	0.224	0.05	0.02	900° C. $\frac{1}{2}$ hr. M. C.	200	2550	7750	12950	13100	13800	15500
						As forged	209	3400	10500	14600	15450	16000	17500
						900° C. $\frac{1}{2}$ hr. M. C.	196	6700	11100	14350	15100	15700	16850
						As forged	196	6700	11100	14350	15100	15700	16850

- (4) Chromium in 3 per cent nickel steels tends to produce inferior results.
- (5) There does not appear to be much to choose between air cooling from the annealing temperature in straight carbon steels, and the same treatment followed by a low temperature tempering, so long as the required mechanical properties are obtained.
- (6) Even with the same analysis and heat treat, variations in magnetic results are to be expected. One cannot find an explanation of these variations. There are so many unknown factors which might affect the magnetic properties.

In order, however, to obtain a better idea of the influence of composition and heat treatment, Table X has been included. This table contains the results obtained on material treated in the form of bars $\frac{3}{8}$ inches in diameter. The influence of carbon and nickel, as stated above, is clearly shown. In all cases, slow cooling from the annealing temperature (cooling down with the muffle) gives the best magnetic results, although there is a tendency for the air-cooled condition being slightly better in high magnetic fields, except in the case of the nickel-chromium steels, where, owing to the tendency to air-harden, inferior results are obtained when the material is air-cooled from the annealing temperature. Table X also includes the influence of elements other than those usually used in forgings of this type. From these it may be inferred that 1 per cent of copper is practically without influence on the magnetic properties, while 1 per cent of manganese is detrimental, especially in low fields. Increasing the silicon in these materials to 1 per cent does not produce superior magnetic results, even in low magnetic fields, the indications on the other hand are the reverse. Chromium is definitely detrimental, while $2\frac{1}{2}$ per cent of cobalt, though not appreciably affecting the results in low magnetic fields, gives superior values in high magnetic fields.

Nonmagnetic Steels

There is a limited call for nonmagnetic steels, and, from the practical point of view, the following steels are of interest:—

- (1) 14 per cent manganese steel
- (2) 25 per cent nickel steel containing a little chromium
- (3) Manganese-nickel steels
- (4) Manganese-nickel-chromium steels
- (5) Austenitic chromium-nickel steels

The difficulty of machining manganese steel places that material at a disadvantage. The austenitic chromium-nickel steels are very effective, but have a low yield and can be considered costly. The steels most in vogue are the nickel steels, the manganese-nickel steels and, more recently, the manganese-nickel-chromium steels.

Steels of Low Coefficient of Expansion

The only steels of interest are the high nickel steels, and they have been so adequately dealt with by Circular No. 58 of the Bureau of Standards that there is little left to be said. The 35 to 36 per cent nickel steel has found a limited though extremely valuable application, and is a very interesting steel.

The coefficient of expansion of invar is 1.19×10^{-6} per degree Cent., but this value is reduced by heating followed by rapid quenching, and also by cold work. It is possible by quenching a rod and then tempering it to the limit to reduce the coefficient by an amount 1.5×10^{-6} , that is to a negative value. If the material is then reheated for several hours at 100 degrees Cent., the coefficient is raised to nearly zero. Invar, with change of temperature, does not assume a steady state immediately. It appears that there is always a tendency to change its length in the direction from which it has come. Thus a meter length which has been brought to 100 degrees Cent. immediately after forging increases in length at about 0.067×10^{-4} centimeters per minute, while if it is brought to 100 degrees Cent. after remaining at room temperature for a considerable time, it will contract at the rate of 0.8 to 0.9×10^{-4} centimeters at 15 degrees Cent., the elongation is 0.07 to 0.08×10^{-4} centimeters per day after forging, and 0.03×10^{-4} centimeter per day after annealing to 40 degrees Cent. Again, after a long rest at room temperature (10 to 20 degrees Cent.) the contraction that occurs after assuming a higher temperature is complete in about $\frac{1}{2}$ hour at 100 degrees Cent. but continues for several days at 40 degrees Cent.

Apart from these changes in length following sudden changes in temperature, there are also other changes that continue for a long time while the temperature remains constant. Thus a bar of invar left to itself at any constant temperature elongates slightly, at first rapidly, then more slowly until it gradually reaches a steady length. The higher the temperature, the sooner this steady

condition is reached. In order to reduce these secular changes to a minimum Guillaume employs an aging process consisting of heating at gradually decreasing temperatures, starting at 100 degrees Cent. and ending at 20 or 25 degrees Cent. for periods of two to three months. These variations must be taken into account when very accurate measurements need to be made with the use of invar measuring tapes.

Invar melts at 2597 degrees Fahr. (1425 degrees Cent.), has a density of about 8.0 grams per cubic centimeter, an electrical resistivity of 85 microhms per centimeter cube, with a temperature coefficient of 0.0012 per degree Cent., and is ferromagnetic, but becomes paramagnetic in the neighborhood of 329 degrees Fahr. (165 degrees Cent.). The low expansion of invar only applies below 200 degrees Cent., above which it has an expansion nearly that of Bessemer steel. The mechanical properties of invar are approximately as follows:—

Maximum Stress, pounds per square inch	49300 to 98600
Yield, pounds per square inch	29100 to 71700
Elongation, per cent	25 to 50
Reduction of Area, per cent	40 to 70
Brinell hardness number	160

The steel containing this nickel percentage of 35 to 36, with an addition of 12 per cent of chromium, is of great interest as having the property of invariable modulus of elasticity over a limited range of temperature.

The only other alloys of which the author has experience, which are of interest because of their low coefficient of expansion, are those containing 46 per cent, 44 per cent and 42 per cent of the element, the varying nickel content resulting in slightly different, but sometimes desirable values of the coefficient of expansion. Subsequent investigations do not appear to have improved upon the original work of Guillaume in this field.

Steels of High Electrical Resistance

While the resistivity of steels of various compositions has been determined, it cannot be said that such steels are in great demand. The iron-nickel-manganese steels and the iron-nickel-chromium steels contain useful combinations; whilst chromium-silicon and chromium-aluminum steels, particularly the latter, are shown to

be of value from this standpoint. It is desirable in some cases that the characteristic of high resistivity shall be accompanied by the non-scaling property and substantial strength at the high temperatures, and from this standpoint some of the acid-resisting chromium-nickel steels and the chromium-nickel-tungsten heat-resisting steels may possibly prove to have quite a future.

Causes of Failure

Reliability has already been mentioned as a preeminent characteristic, and it is hoped to discuss such aspects of steel metallurgy as bear upon the subject, since even the most costly alloy steel, perfectly heat treated, is useless unless that essential feature is obtained. As regards failures in service, experience shows that there is frequently some obvious cause. Whether or not the cause is obvious, it is, of course, existent. The fugitive nature of the explanations of some failures demands a careful analysis of possibilities. While discussing failures in service, it is well to point out that the explanation of failure is frequently assisted by examinations of examples which have done excellent service. Too little examination is made of the latter, and it is frequently the case that many features of failures are considered to be bad ones, which would most likely be cancelled out by the same features being discovered in excellent samples. When cases come to the author for investigation, the following procedure is adopted. In the first place, the design of the part and its relation to other parts in the mechanism in which it serves, are carefully studied, together with the actual conditions of service, that is, the magnitude and manner of the stresses the part is called upon to withstand. In this preliminary investigation, some idea is obtained as to the possible mechanical causes of failure. The manner in which such failures would be assisted by inherent undesirable characteristics in the steels is next investigated. The chemical composition is determined to indicate the quality of the steel; the microstructure is examined to determine the thermal treatment to which it has been submitted, and the macrostructure is developed with a view to determining the homogeneity of the mass. The mechanical tests, including an adequate selection of those available, are performed. For purposes of comparison, a companion examination of a successful part is put through wherever possible.

As a result of numerous investigations, failures seem to place themselves in different categories. Treating the matter broadly, there are two types. In the first one, failures would be included where the material has rightly been assumed by the engineer to possess strength and freedom from defects, but when the material, unfortunately, did not merit his confidence, that is, the material has failed to live up to reasonable expectations. In the second category would be placed the wide range of cases where subsequent examinations have shown the material reasonably to possess properties which the engineer associated with it, but where failure has obviously been due to insufficient knowledge, or to too empirical treatment on the part of the engineer with regard to the stresses with which he had to deal. In the first category, one would include cases where the steel is put to work in the wrong condition; where it has received faulty heat treatment; where it has been put to work in an unstable condition; and, lastly, where the part has been placed into service containing undiscovered actual defects. In the second category, one must include bad design; imperfections of the technique and production; abnormal stressing (shock, deformation leading to over stressing, etc.); an imperfect knowledge of the full properties of the steel by the engineer; and, lastly, an imperfect knowledge of the distribution of stress in the parts under consideration. Failures may come under either category, i.e., the steel may be well below the requirements in strength from one cause or another, or the part may be too weakly designed to withstand the type and magnitude of stresses which have to be encountered. There are two further sources of failure which it is considered should also come under the second category, viz., wear and corrosion. The lecturer recently investigated a very serious case where the failure of a shaft, through corrosion, would have been prevented had the engineers responsible appreciated the more simple causes of corrosion.

SECTION V

CORROSION AND ACID RESISTING STEELS

Today, there are alloy steels available which are truly rust resistant, and others which are so successfully resistant to the attack of certain acids as to have led to revolutionary changes in the

construction of chemical plant. The author is old enough to remember the time when the metallurgical world was in a state of mind, which, to say the least, was pessimistic as regards the possibility of producing such steels. The discoveries were made and subsequent to the essential discoveries came the explanation of the phenomena.

Induced passivity had first been observed by J. Keir¹²⁰ so long ago as 1790; in so much as he had observed that iron, after treatment with concentrated nitric acid, had lost the property of precipitating silver from solutions of silver salts, and was no longer attacked by dilute nitric acid. The great Michael Faraday, whose intellect was so profound, and whose insight was so great as to enable him to give us the key to many of Nature's latent faculties to serve us, gave us in 1836¹²¹ by insight the true explanation of such passivity. He reasoned that all known passivity phenomena are oxidation processes and visualized that "the surface of the iron is oxidized or the superficial particles of the metal are in such relation to the oxygen of the electrolyte as to be equivalent to oxidation." It was left to my friend Ulick R. Evans at Cambridge to establish nearly a hundred years later the existence of such a film by actually isolating it. Some eighteen months ago, the author visited Evans in his laboratory and there actually saw this "hypothetical" film under the microscope. The polishing marks of the outer surface of the metal were definitely to be seen on the gosamer-like patches of films which were floating under the objective. "Are they actually oxide of iron?" the author said, and Evans at once caused the reaction and the films turned blue. It may be imagined how deeply impressive was this experience. Here was the complete demonstration of the accuracy of the view held by both of us, that passivity was to be explained by the existence of this film. Some few years previously¹²² we had made an interesting discovery at the Brown-Firth Research Laboratory which had led us definitely to take that view. We had found that 14 per cent chromium steel, which is rapidly soluble in 10 per cent sulphuric acid, was temporarily passive to that acid after it had been immersed in nitric acid which apparently had no effect upon it.

¹²⁰J. Keir, *Phil. Trans., Royal Society*, Vol. 80, p. 359.

¹²¹Michael Faraday, *Phil. Magazine*, Vol. 9, p. 53.

¹²²W. H. Hatfield, *Engineer*, December 15th, 1922.

Obviously, some profound change in the surface condition must have been effected. It is considered that Evans' isolation of the oxide film¹²³ is a fundamental and, indeed, monumental piece of work, and it definitely provides a basis for further discovery, deduction and development.

Vernon¹²⁴ has shown that a gauze screen some distance from the specimen will prevent rusting in the London atmosphere. This is a marked advance also.

In view of such facts, the author would turn to the consideration of the question as to why iron rusts. May it not be that iron protects itself by immediately forming the protective film when brought in contact with certain oxidizing media, and that failure to resist, i.e., progressive "oxidation," results from the puncturing and local destruction of this film through various causes—from causes such as the presence of particles of foreign matter leading to damage through local electrolytic effects; from local concentration of corroding media in dew effects, etc. Incidentally, a continuous protective film presupposes a continuous metallic surface for it to form upon, and what with the dispersion of oxide or silicate inclusions of indeterminate composition, and the actual unsoundness of the bulk of steel produced, even in America (see Figs. 9 and 11), it cannot be considered that such a condition is fulfilled. The author is of the opinion that ordinary commercial steel can, in itself, be much improved as regards its resistance to corrosion by the extension of our knowledge and application of the laws of physical chemistry where they bear upon steel production from the standpoint of the manufacture of material free from oxides and gas holes. He understands that in America claims are being made that, irrespective of these considerations, the addition of a little copper improves the steel. This he is interested to hear, but hopes to have the opportunity, during this visit to the United States, of studying the evidence upon which such claims are made.

In reheating and during rolling, the external oxide layer is formed upon the steel, and attention to the time-temperature effect, coupled with control of the nature of the furnace atmosphere, cannot be without influence upon the characteristics of the surface as regards resistance to attack. There is a field for investigation of the greatest importance.

¹²³Evans, *Transactions*, Chemical Society, 1927.

¹²⁴Vernon, *Transactions*, Faraday Society, April, 1927, pp. 113-185.

The corrosion of ordinary ferrous materials has received much attention from U. R. Evans, and the author would suggest reference to a series of five extremely useful papers¹²⁵ dealing with the use of inhibitive chemicals, protective coatings, formation of rust, corrosion of wrought iron as against steel, and the corrosion and contacts of dissimilar metals. These papers state the present position very well.

It cannot be said that the early attempts to explain corrosion effects were successful in accounting for all the subsequently observed facts. Failure of metals by corrosion, particularly in the case of steels, has, as one of its chief features, the local effect of pitting. It cannot be said that, previous to the researches of Evans and Bengough, we had any satisfactory idea of the mechanism of this form taken by the attack. The old electro-chemical theory of corrosion proved incomplete when it was found that some of the most resistant steels and alloys were heterogeneous in character (Stainless steels, Nichrome¹²⁶), but even such heterogeneous resistant materials fail in certain corroding media by the local pitting effect. In an excellent review of the whole subject, Carpenter¹²⁷ traces the development of the new electro-chemical theory, and reminds us that as early as 1830, Marianini, and later, Warborg and Kistiaskowsky, showed that currents could be generated by variations in oxygen concentration in the corroding media. The further investigations of Aston, Evans, McKay and Bengough, particularly the work of Evans and Bengough, can be said to enable us to visualize the process of pitting in a way that was not previously possible. It is difficult to be certain as to the cause of this type of corrosion in all cases, but it seems reasonable to assume that the two conditions required are, firstly, a medium which either does not, or which only just attacks the chief constituent of the metal when pure and under anaerobic conditions, and, secondly, some factor or factors leading to local acceleration of attack. If the first condition is not satisfied, any tendency to pitting will be more or less masked by general attack, and if the second does not apply, the attack will be even. It remains to fix the cause or causes of the

¹²⁵U. R. Evans, *Journal*, Society of Chemical Industry, Vols. XLVI and XLVII.

¹²⁶W. H. Hatfield, *Engineer*, December 15, 1922.

¹²⁷Carpenter, James Forest Lecture, Institute of Civil Engineers, 1927.

Table XI

Iron	Hydrochloric Acid		Nitric Acid		Sulphuric Acid	
	Normal	Concentrated	Normal	1.20 Sp. Gr.	Normal	10 per cent
Electrolytic	0.0085	0.0860	0.1147	0.7261	0.0057	0.0068
Armco	0.0116	0.1385	0.1406	0.7592	0.0099	0.0152
English wrought	0.1416	0.2217	0.1263	0.6399	0.1452	0.3610
Analyses Per Cent						
C	Mn	Si	S	P		
0.025	nil	0.04	0.009	0.004		
0.06	0.01	nil	0.029	0.007		
0.03	0.145	0.07	0.01	0.193		

local acceleration, and the following, in the light of present knowledge, are suggested as probable:—

- (1) Small areas less accessible to oxygen than the surrounding material will become anodic to the rest of the material, and a condition favorable to pitting will exist. Small surface defects and extraneous foreign bodies may cause trouble in this way.
- (2) If a metal is normally covered by a protective oxide film,

Table XII

	Carbon	Per Cent Silicon	Chromium	Brinell No.	Concentrated HCl	HNO ₃ Sp. Gr.	H ₂ SO ₄ 10 per cent
						1.20	
1.	0.08	0.56	10.08	230	0.0148	nil	0.0722
2.	0.07	0.73	13.26	185	0.0297	nil	0.2027
3.	0.07	0.77	15.96	141	0.0416	nil	0.2763

small defects in this film, however caused, may produce local decrease in resistance, leading to pitting.

- (3) Local concentration of corroding medium (moist crystals, etc.)
- (4) If a material has small areas differing in some way, either chemically or physically, from the mass of the material, then such areas may supply the accelerating force, either by electro-chemical means, if they are anodic to the rest, or possibly by virtue of the fact that they are not so chemically resistant to the medium.

One of my predecessors in this lecture, Dr. Guertler,¹²⁸ reviewed generally the resistance of industrial metals, and his concluding remarks were—"Seventh; the last point is: we must never

¹²⁸W. M. Guertler, "The Corrosion of Metals," TRANSACTIONS, American Society for Steel Treating, Vol. XIII, No. 5, 1928, p. 759.

expect to find a permanently durable alloy which will be universally resistant to all reagents, but we may reasonably expect a very beautiful development of alloys, each of which has its own special application. Nor is it likely that we will find an alloy which will resist every kind of chemical reagent in the same way. According to the solubility or nonsolubility of the different chemical compounds which may form on the surface, one alloy will be better for one reagent, and another alloy will be better for a different reagent." The matter could not be stated more simply or more accurately, and the author proposes now to follow up that phase of the matter as regards the recent development of rust and acid-resisting steels.

In the first place, iron is the base metal upon which the steels are built, and minor differences in its purity and method of manufacture are reflected in the resistance to acids, and shown in the results given in Table XI.

Over the last century, many attempts were made to provide corrosion-resisting steels by means of added elements, but the method of comparing the resistance was generally that of immersion in sulphuric acid, or some similar medium, which our present knowledge shows could not have led to the epoch making discovery of chromium rustless steels. Such steels were cast, but the methods employed failed to detect their latent corrosion-resisting properties which could be developed by heat treatment. The influence of chromium is now believed to be that of producing the necessary resistance through the creation of a satisfactory oxygen-containing passivity-producing film. As shown by the following data, the presence of chromium gives no protection to sulphuric acid; on the contrary, the steel becomes more readily soluble as the chromium increases (Table XII).

Corrosion Tests

In all methods of submitting metals to experiments designed to arrive at definite knowledge in regard to resistance to corrosive attack, there are disturbing factors which either accelerate or retard the action. Usually the tendency is to accelerate the action. There is primarily the manner in which the specimen is either suspended in the corrosive medium, or in the other case the manner in which the sample is supported. Contact with some solid

body, different in composition from that of the metal to be tested, is inevitable, and electro-chemical action is set up, which involves the issue.

There is the question of oxygen supply to the corrosive areas. If the sample is exposed to normal atmospheric oxidation, the amount of moisture is relatively small, and the amount of oxygen is large, so that the surface of the steel is constantly bombarded with oxygen atoms. If, on the other hand, the sample is totally immersed in a liquid, (for example, sea water), there will be different degrees of aeration at different points of the specimen, i.e., the top portion will be well supplied with oxygen, whilst the portion which is supported by the containing vessel will be relatively free from oxygen. It has been proved by Evans that differences of potential are set up by differential aeration, the aerated portions suffering cathodic protection, while the nonaerated portions are anodic and are attacked. This most probably explains why so many test pieces corrode "in contact with the glass of the containing vessel" when totally immersed in saline and other solutions.

In the case of samples partially immersed, there is frequently marked acceleration in attack at the liquid level. In a case where the sample is tested in a liquid in motion, such as in the typical example of running water (tap water), the rate of flow has a marked effect upon the rate of corrosive attack (as shown by Dr. Friend). In the statement, of corrosion tests, in terms of change in weight per unit of surface area, a possible error arises, in that there is often a loss due to solution of the metal and a gain due to oxidation. Endeavors to remove adherent rust by means of reagents have not proved successful. In testing corrosion-resisting alloys, a visual inspection will convey more exact information on the comparative values of particular alloys than any written work. In testing in corrosive agents, such as mineral acids, results can only be comparative, since if action does take place, the solution of the metal automatically weakens the strength of the reagent. The physical state of the metal is also of paramount importance. (a) Its surface condition, rough or smooth, (b) degree, if any, of cold work, (c) the heat treatment it has undergone.

The data presented in this section, unless otherwise stated, have been obtained from experiments conducted under reasonably uniform conditions and are, therefore, comparable. In all cases,

the specimens weighed about 35 grams and were cylindrical, having a diameter of about 1.25 centimeters. The specimen was totally immersed in a standard volume of the liquid (70 to 80 cubic centimeters). In each case a standard polish was given to the specimen, i.e., the finish resulting from the use of 00 emery. Where quantitative results are given, the figures indicate the loss in weight per square centimeter of surface for the time of exposure to the corroding media.

The author finds it difficult even to attempt to deal with the chromium and chromium-nickel rust and acid resisting steels in a short section of this lecture, as will be understood when it is realized that during the last few years some 15,000 to 20,000 corrosion tests have been made in the Brown-Firth laboratories. The steels are now established in Britain and are continually being applied to new and diverse purposes, and this necessitates an exten-

Table XIII

Metal	HCl (Conc.)	H ₂ SO ₄ 10 per cent	HNO ₃ Sp. Gr. 1.20
Iron	0.0814	0.0327	0.7165
Nickel	0.0037	0.0002	0.1546
Chromium	0.2014	0.0014	0.9906

sive system of research as regards a very wide range of corroding media, and an exploration of all their physical properties. It will be appreciated that the exploration and description of the characteristics of one steel of a given analysis is a large undertaking, and in the chromium and nickel-chromium series there are several which have proved of marked industrial value, but which have widely different corrosion-resisting and physical properties. That is, of course, a great boon, since it is found that almost all the physical characteristics required for the many different functions, accompanied by adequate resistance to corrosion, can be obtained by suitably varying the analysis and treatment of the steel. The main credit for the development of these steels is due to the Krupp and Brown-Firth research laboratories. Strauss approached the field by adding chromium to nickel steels. Brearley gave his attention to the chromium steels and developed the stainless steel. It has been one of the author's great pleasures, during recent years, to assist in continuing the development of the steels, and

Table XIV

Condition	Brinell No.	HCl concentrated	HNO ₃ Sp. Gr. 1.20	H ₂ SO ₄ 10 per cent
Normalized	167	0.1812	0.5858	0.1032
As rolled	157	0.3075	0.8989	0.2198
	180	0.1666	0.0005	0.3048
	180	0.1492	0.0001	0.2143
	209	0.1845	nil	0.2496
	255	0.2902	nil	0.4279
	223	0.1709	nil	0.3530
	209	0.2836	nil	0.4543
	216	0.3221	nil	0.5583
Per Cent				
C	Mn	Ni	Cr	Si
0.395	0.66	0.41	nil	0.19
0.38	0.18	0.10	5.10	0.09
0.64	0.34	0.15	8.96	0.19
0.29	0.22	0.09	10.06	0.14
0.56	0.21	0.10	12.47	0.12
0.50	0.35	0.11	15.6	0.28
0.49	0.21	0.14	19.66	0.23
0.53	0.30	0.10	24.22	0.38
0.58	0.31	0.15	32.07	0.49

he has no hesitation in saying that the field is by no means exhausted. In Europe, the chromium rustless steels are generally based upon a chromium content of 13.0 to 14.0 per cent, with a variable carbon content according to the use to which they are to be put. The chromium-nickel acid-resisting steels are generally within the range of 12.0 to 25.0 per cent chromium and 5.0 to 15.0 per cent nickel, but it will be appreciated that within such a range there are steels of widely different characteristics. Incidentally, it may be mentioned that, in addition to the nickel and chromium, such elements as molybdenum, copper and others, are at times alloyed in the steels. As will be clear, the idea of each modification in composition is to make the individual steel more resistant to some particular corroding media.

Multiplication in the manufacturing specifications of the steels is a disadvantage in production, since output is a determining factor, not only as regards technique and cost, but also from the standpoint of supply, and the result has been to select, as a result of research, one or two compositions of outstanding merit, and then to specialize in their production; subsequently introducing into their manufacture such improvements as later research may dictate. It follows, therefore, that the technology of some of these steels may have developed upon different lines in America, and this the author thinks is the case, particularly as regards the plain chromium stainless steels.

Reverting to the earlier experimental work. The essential elements concerned are iron, chromium and nickel, and it is of interest to study the response made upon immersion in nitric, sulphuric and hydrochloric acids at normal temperatures. This can be done by reference to Table XIII and it will be seen that the essential features are the excellent resistance of chromium to nitric acid, and the resistance of nickel to sulphuric acid.

A reference to Table XIV enables the response of industrial alloys of the iron and chromium to be studied, and it will be seen that when the chromium reaches 10 per cent, the alloy has become remarkably resistant to nitric acid, while, curiously, the resistance to sulphuric acid decreases. It is interesting to study a series of similar experiments with iron-nickel alloys. This is possible upon reference to Table XV, when it will be seen that increase in the nickel content reduces the solubility in sulphuric and hydrochloric acids, but that the whole series is readily soluble in nitric acid. A study of the response of a series of alloys containing both chromium and nickel in varying proportions now becomes of very great interest, and this can be done by reference to Table XVI. Generally speaking, it will be seen that, as regards resistance to nitric acid, the presence of nickel is additive to the influence of the chromium in increasing the resistance to the acid. At the same time,

Table XV

Condition	Brinell No.	HCl concentrated	HNO ₃ Sp. Gr. 1.20	H ₂ SO ₄ 10 per cent
As rolled	187	0.1142	0.7388	0.0221
	157	0.0872	0.4475	0.0072
	276	0.1593	0.6494	0.0102
	345	0.1939	0.7123	0.0074
	330	0.0816	0.7026	0.0028
Quenched at 1830° F.	198	0.0838	0.6887	0.0010
	168	0.0568	0.7532	0.0008
	175	0.0678	0.5914	0.0006
	186	0.0290	0.7745	0.0005
	157	0.0237	0.5730	0.0003
	117	0.0329	0.5684	0.0004
		Per Cent		
C	Mn	Ni	Cr	Si
0.26	0.41	4.82	nil	0.16
0.16	0.33	6.05	nil	0.41
0.30	0.31	9.02	nil	0.13
0.23	0.18	12.23	nil	0.11
0.32	0.28	14.90	nil	0.12
0.26	0.31	20.08	nil	0.12
0.31	0.98	24.21	nil	0.34
0.18	1.00	26.1	...	...
0.18	1.07	29.3	...	0.25
0.23	0.35	36.50	nil	0.12
0.29	0.57	44.75	nil	0.22

whereas chromium by itself increases the solubility in hydrochloric and sulphuric acids, the presence of nickel leads to an increased resistance to these acids. The figures in this table relate to one concentration of acid and to ordinary temperature without any ap-

Table XVI

C	Mn	Per Cent		Si	HCl concentrated	HNO ₃ Sp. Gr. 1.20	H ₂ SO ₄ 10 per cent
		Ni	Cr				
0.36	0.18	0.10	5.06	0.05	0.3075	0.8989	0.2198
0.36	0.13	5.42	5.06	0.05	0.1763	0.0003	0.0720
0.35	0.16	10.39	5.13	0.03	0.1897	0.0059	0.1329
0.30	0.14	15.27	4.90	0.07	0.0963	0.0001	0.0015
0.36	0.20	20.02	5.05	0.16	0.0367	0.0002	0.0008
0.29	0.22	0.09	10.06	0.14	0.1492	0.0001	0.2143
0.31	0.36	4.88	9.84	...	0.1732	0.0001	0.0689
0.56	0.21	0.10	12.47	0.12	0.1845	nil	0.2496
0.51	0.17	5.23	11.81	0.12	0.1479	nil	0.1321
1.07	0.44	0.13	12.26	0.09	0.1869	0.0004	0.3565
1.16	0.39	5.33	12.84	0.14	0.1747	0.0001	0.2288
1.07	0.32	10.33	12.04	0.24	0.1483	0.0002	0.1444
0.49	0.21	0.14	19.66	0.29	0.1709	nil	0.3530
0.52	0.31	5.40	18.45	0.29	0.1664	nil	0.2825
0.44	0.31	15.15	19.16	0.33	0.0968	nil	0.0015
1.04	0.21	0.22	20.08	0.14	0.2615	0.0001	0.2904
1.09	0.19	5.44	19.48	0.28	0.2826	nil	0.1311
1.01	0.17	14.90	19.21	0.28	0.0904	nil	0.0016

plied heat. In practice, the author has found it necessary, in corrosion tests, to explore fully the effect of concentration and of temperature, and as specific industrial processes are frequently based upon a limited range of concentration and of temperature, some extremely interesting results have been achieved. A steel of a given composition and in a given heat treated condition will, at

Table XVII

Figures = loss in grams per square centimeter of surface area.				
Reagent	Original Sheet	10 Per Cent Reduction	25 Per Cent Reduction	50 Per Cent Reduction
Acetic Anhydride	0.0012	0.0013	0.0014	0.0014
Glacial Acetic Acid	0.0016	0.0023	0.0024	0.0048
B. P. Acetic Acid	0.0020	0.0036	0.0054	0.0062
50 Per Cent Citric Acid	0.0000	0.0000	0.0000	0.0000
Formic Acid	0.0095	0.0072	0.0208	0.0243
Lactic Acid	0.0076	0.0072	0.0077	0.0087
Nitric Acid (Sp. Gr. 1.42)	0.0305	0.0112	0.0092	0.0093
Nitric Acid (Sp. Gr. 1.42) Vapor	0.0087	0.0059	0.0046	0.0022
Saturated Ammonium Chloride	0.0009	0.0026	0.0001	0.0008

times, be found to resist certain strengths and temperatures of acid, a change in the condition of the steel will result in such media not being resisted. It is necessary to perform actual tests in connection with all industrial processes and generally with several steels in different conditions with a view to ascertaining which one

is the most suitable. The industrial testing out is particularly desirable, because, at times, the composition of the industrial reagent may not be identical with the pure form with which most probably laboratory tests might be made. A mass of data has been accumulated in the Brown-Firth laboratories, but as much of this has now been passed into the trade literature of one of the firms with which he is associated, it is not proposed to reproduce it here.

One very important feature of the influence of fabrication of articles and plant from these materials should be discussed. Any given steel is naturally put into its optimum condition, as regards the work it has to do, at the last process of manufacture. In fabrication, it may be cold-worked, and it may be heated to temperatures of convenience. It may be welded.

Cold work, if local, may have serious effects in lowering the local resistance of the steel; if, however, the work hardening is uniform, then this is not necessarily so. An example might usefully be given. Steel sheet (18 gage), containing 18 per cent chromium and 8 per cent nickel, in the fully softened and descaled condition, was cold-rolled to 10 per cent, 25 per cent and 50 per cent reduction of thickness. Samples of each degree of cold rolling, together with samples of the original softened and descaled sheet, were then tested in various reagents at boiling point for a period of 24 hours with the results shown in Table XVII.

The results show that the cold rolling of this steel (up to 50 per cent reduction) has no effect on the corrosion-resistance in 50 per cent citric acid, and little, if any, in acetic anhydride, or in lactic acid up to 25 per cent reduction. The corrosion-resistance is, however, progressively lowered by cold rolling in the case of glacial and B. P. acetic acids, and in the case of formic acid above 10 per cent reduction. On the other hand, the corrosion-resistance is progressively raised by cold rolling towards nitric acid (sp. gr. 1.42) and the vapor from this acid. The results for ammonium chloride are somewhat irregular, but, in a general way, they indicate that cold rolling has little effect on the corrosion resistance in this medium.

However, local cold work which is considered deleterious, as stated above, cannot always be avoided, but such regions should always be watched.

Heating during fabrication should be always done in a knowl-

edgeable way, having in mind the effect of various temperatures upon the resistance of the material. For instance, the austenitic nickel-chromium steels are put into their best condition by cooling from a high temperature, 2100 to 1740 degrees Fahr. (1150 to 950 degrees Cent.), the actual temperature varying with the composition. Subjection of such steels to low red heat reduces their resistance in certain corroding media.

Turning now to welding, it is, of course, obvious that the steel used for melting into the weld must have finally the same composition as the parts that are being welded. Neither oxidation nor carburization is permissible, since if the composition is modified, so will be the response to the corroding medium, and this is very important in certain critical corroding reagents. In certain cases it is very desirable to re-heat treat after welding. Sufficient has been said concerning these fundamental points to emphasize their importance.

Mechanical and Other Properties of the Steels as Affecting Their Application

The corrosion resisting steels now commercially available are substantially either chromium steels or chromium-nickel steels. In this section, the author will confine his remarks to those steels which are most widely used¹²⁹, and will endeavor to deal with those two aspects which, as far as engineering is concerned, are equally important with the corrosion resisting characteristics, viz., mechanical properties and capacity for being fashioned to the shape required.

The steels which will be considered are:—

- (1) The 12 to 14 per cent chromium stainless steels as used for cutlery and allied purposes.
- (2) The 12 to 14 per cent chromium stainless steels as used for turbine blading and general engineering purposes.
- (3) The 12 to 14 per cent chromium so called "stainless" iron.
- (4), (5) and (6) Austenitic nickel-chromium steels.

The chromium steels (1), (2) and (3) are of the same class, and if heated to a temperature of 1740 to 1830 degrees Fahr. (950 to 1000 degrees Cent.), they harden, roughly, in proportion to the carbon content. They may be, and, in practice, are hardened, and

¹²⁹There are some hundreds of patent specifications covering widely different compositions, including those granted to Benno Strauss and to Harry Brearley, whose work has been referred to herein.

Table XVIII

	Steel	Analysis								Tensile Properties					
		C	Mn	Si	S	P	Cr	Ni	Limit of Proportional- ity, lbs. per sq. in.	Yield Point, lbs. per sq. in.	Maximum Stress, lbs. per sq. in.	Elongation, Per Cent	Red. of Area, Per Cent	Isod Impact Test, foot-pounds	Ericksen, m. m. (18-gage sheet)
1	Cutlery Stainless Hardened 1760° F. Tempered 356° F.	0.30	0.30	0.20	0.015	0.015	13.0	0.30	.....	.....	237,400	...	...	..	..
2	Stainless (Engineering purposes) Hardened 1760° F. Tempered 1382° F.	0.30	0.30	0.40	0.015	0.015	14.5	0.30	60,500	72,300	108,400	27.6	63.6	52	...
3	Stainless Iron Annealed 1562° F. H. 1700° F. T. 1292° F.	0.09	0.18	0.14	0.015	0.015	13.4	0.28	29,100	35,600	67,400	40	75	96	9.7
4	Austenitic (a) fully softened	0.15	0.28	0.29	0.016	0.017	14.8	10.9	53,800	72,300	92,500	26.5	65.7	100	...
5	Austenitic (b) fully softened	0.14	0.30	0.30	0.015	0.016	18.1	7.9	24,600	29,500	83,500	66.5	68.0	110	15.5
6	Austenitic (c) fully softened	0.28	0.30	0.16	0.02	0.02	21.0	5.8	27,300	34,700	100,800	71.0	62.0	110	16.0
	H = Hardened. T = Tempered.								33,600	47,000	116,500	55.0	58.0	84	13.0

then can be subsequently softened by tempering to the requisite condition of mechanical strength desired. These are martensitic steels.

The chromium-nickel steels (4), (5) and (6), are in a separate class and have the distinctive characteristic that, if they be heated to a high temperature and quenched, they do not thereby become hardened, but instead are put into a very ductile condition, i.e., they are austenitic steels. In Table XVIII will be found typical tensile, impact and Erichsen figures, determined in the Brown-Firth research laboratories, for these steels.

The Chromium Steels (1) to (3). This class of steel can be considered as responding to heat treatment in a similar way to the widely used alloy steels, and it will be agreed that the tensile values are in accord with this. The typical steel of this class is one containing approximately 0.30 per cent carbon, and, in the form of cutlery, the necessary hardness is readily obtained by hardening from 1740 to 1830 degrees Fahr. (950 to 1000 degrees Cent.), and tempering to 360 to 390 degrees Fahr. (180 to 200 degrees Cent.). The tensile values (1) correspond to this form of the material.

The similar steel (2), which is used for general high tensile engineering purposes, is put into the mechanical condition indicated in the table, by hardening followed by suitable tempering, in which form it is supplied. In the condition given, it may be machined with reasonable ease, and is widely used with success for parts required to resist atmospheric corrosion, superheated steam and many other conditions too numerous to mention. It is clear that the next mechanical condition of rustless steel required by the engineering and the industrial world was that in which it could easily be deformed cold to shape, and the steel given as (3) indicates the degree of success attainable by lowering the carbon content. It must, however, be confessed that, whilst relative success was achieved by modifying the plain chromium rustless steel in this way, it was found that the chromium-nickel austenitic steels (4), (5) and (6), the figures for which are given, fulfilled more completely this particular demand of the industrial world.

The Chromium-Nickel Steels (4), (5) and (6)

Besides their much greater resistance in a wider field of cor-

Table XIX

	Steel	Analysis						Specific Gravity	Coefficient of Expansion, 20-200° C., Per. °C.	Specific Heat, 0-100° C., gr. cal. per sq. cm.	Thermal Conductivity, 20-100° C., cal. per sq. cm.	Electrical Resistivity, microhms cm. cube	Maximum magnetic Permeability
		C	Mn	Si	S	P	Cr	Ni					
1	Cutlery Stainless Hardened 1760° F. Tempered 356° C.	0.30	0.30	0.20	0.015	0.015	13.0	0.30	0.0000097	0.115	0.043	65	75
2	Stainless (Engineering purposes) Hardened 1760° F. Tempered 1392° F.	0.30	0.30	0.40	0.015	0.015	14.5	0.30	0.0000109	0.117	0.050	54	650
3	Annealed Iron H. 1766° F., 1292° F.	0.09	0.18	0.14	0.015	0.015	13.4	0.28	0.0000110	0.115	0.046	56	500
4	Austenitic (a) fully softened	0.15	0.28	0.29	0.016	0.017	14.8	10.9	0.0000110	0.115	0.044	56	400
5	Austenitic (b) fully softened	0.14	0.30	0.30	0.015	0.016	18.1	7.9	0.0000180	0.117	0.032	74	1.01
6	Austenitic (c) fully softened	0.28	0.30	0.16	0.02	0.02	21.0	5.8	0.0000177	0.117	0.033	69	1.01
									0.000017	0.118	0.035	67	1.01

H. = Hardened. T. = Tempered.

roding influences, it will be seen that they possess a much greater ductility, and, therefore, capacity for plastic deformation than the plain low carbon chromium steels. The heatings sometimes necessary in manipulation do not lead to the air hardening difficulties so well known by those engaged in manipulating alloy steels.

Perhaps, from the mechanical testing point of view, the distinctive feature of these steels, when compared with the plain chromium steels, apart from their high ductility as disclosed in the tensile test, is their high impact value, which is generally in excess of 100 foot pounds when determined by the Izod form of test under British Standard conditions.

As regards the general physical properties, the data given in Table XIX will be of interest. A survey of this data indicates marked dissimilarities, as regards physical properties, as a result of the increase in chromium and the addition of nickel, in the case of the chromium-nickel steels. This is particularly noticeable in the increased coefficient of expansion, and in the thermal conductivity; these factors must, of course, be taken into consideration by engineers when applying the material to conditions where elevated temperatures are obtained. Another outstanding and marked characteristic is the nonmagnetic nature of such materials.

Concluding Observations

The author trusts that the foregoing data has made it perfectly clear that the rust and corrosion resisting steels now available are the logical outcome of patient investigation, and that their characteristics are firmly established by unquestionable experimental evidence. He also trusts that, within the scope of this section, he has given a sufficient indication of the mechanical and physical properties of these various steels to enable the engineer, in his own mind, to consider their spheres of application.

As regards the stainless steel (1), used for cutlery, no comment is here required.

As regards the stainless steel for general engineering purposes (2), this is now widely applied for several purposes in engineering, notably—turbine blading, pump rods, superheated steam castings and other purposes too numerous to mention. One very interesting application might be mentioned, namely—the production of sluice gate castings in this composition. Sets of dock sluice gates

were cast for one of the big dock authorities in England, and were actually put into operation in estuary water over four years ago. On examination recently, the interesting fact was disclosed that they were completely unaffected by the obvious corroding influences to which they had been submitted.

The lower carbon-chromium steels are used in a limited degree both in bar and sheet form.

The chromium-nickel steels, however, as explained, have so many advantages when considering those spheres of application where great ductility is required, that it might perhaps be well here to discuss the applications in more detail. The author has a motor car, the whole of the bright fittings of which are made in austenitic steel (2). They are only washed occasionally and are a perfect success, in spite of the fact that they "move and have their being" in the industrial atmosphere of Sheffield. Large chemical plants are operating successfully, which are made of this steel. Dental fittings for tens of thousands of people have been made from austenitic steel (3). Domestic ware in large quantities is in service made from all of them. Nothing further, therefore, need be said.

It will, no doubt, be asked what the possibilities are of these steels as regards general application. Their future will largely be determined by their cost of production. Considerable output is necessary to obtain a low cost of production, and while the application to various purposes is being rapidly extended, the forms in which the steel is required naturally differ greatly. It is, therefore, clear that until the consumption of steel results in even greater demands of a given form and size, be it sheet, bar, section, wire or tubes, the cost of handling, as regards production in the works, must necessarily remain relatively high. There is also another aspect which can be usefully emphasized, namely—that to be satisfactorily rust-resisting, it is necessary that that surface shall be free from defects and scale, and, therefore, this consideration demands a high standard of technique in manufacture of the finished article. It is thus obvious that the production of the rustless and acid resisting steels should always be conducted under the best technical control, which control must be emphasized at each stage of manufacture if the desired result is to be obtained. When considering this question of production, it is necessary to re-state

that these steels contain high proportions of special elements, such as chromium and nickel, and thus the cost of adding these elements must necessarily have its influence upon the economic questions arising. It is true that very considerable metallurgical investigation is, at the present time, in hand with a view to meeting this aspect of matters, but the author feels that one must not lose sight of the fact that Nature herself has put a limit to this manner of making steels rustless. The world's production of steel runs up towards a figure of 100,000,000 tons per annum, whilst its production of chrome ore is, at the present time, somewhere in the neighborhood of 250,000 tons.

Concluding this survey of the development of steels resistant to corrosion, the author would observe that there is undoubtedly a great future in their application. They will, however, always be "special" steels, and although, owing to their relatively high cost, they will not be employed for purposes where ordinary steel is sufficiently satisfactory, yet the demand will be very large. Undoubtedly, the industrial world is now furnished with a very valuable series of steels, added to the already existing special steels that had been developed during the last few decades.

SECTION VI

EFFECT OF TEMPERATURE UPON STEELS

(Including a Treatment of Heat Resisting Steels)

The development of higher pressures and temperatures in steam production, the call for steels having high strength and chemical resistance at elevated temperatures in the chemical industries, the general problem of exhaust valves and other demands, have made the study of the characteristics of steels at high temperatures of first importance. If the designer is to devise plant and machinery which can be safely operated at higher temperatures under diverse influences, the effect of those conditions upon the characteristics of the steel must be completely determined, and the designer given such concrete and reliable information that he may be able to apply the necessary factors of safety. The call for such data is imperative. Both in America and in Europe, capable investigators are attempting to explore this field successfully, but it is quite clear that some time must elapse before the data can be

available. The delay is due to the well recognized difficulty of dealing with the time effect. Chevenard,¹³⁰ Dickenson,¹³¹ Lea,¹³² Tapsell and Bradley,¹³³ Brown,¹³⁴ Jasper,¹³⁵ White,¹³⁶ Kanter and Spring,¹³⁷ French, Cross and Peterson,¹³⁸ and others, by substantial contributions to our knowledge in this field, have given us a sound foundation upon which to build.

To recapitulate the position, and the author feels entitled to do so, owing to the contribution which the Brown-Firth research laboratories are endeavoring to make to the subject, it is proved that steels may be plastically deformed by stresses imposed over long periods, which would be without measurable effect when imposed over short periods. Clearly, the first problem is to determine the value of stress which can be borne indefinitely without plastic deformation.

In a recent paper,¹³⁹ the author has discussed this question, and has expressed, or rather restated, the view that steels must have an elastic range, i.e., a range of stress within which they behave as practically elastic bodies. This follows from the fact that they are crystalline aggregates, and it holds good for the crystalline phase irrespective of temperature, or, how would the atoms orientate themselves to the space lattice? It is quite clear that a stress of a certain magnitude must be applied to destroy the lattice, otherwise it will persist. At low temperatures, the order of stress required is relatively high; at high temperatures, it is only nominal. When cohesion is overcome, plastic deformation results. Our difficulty today lies in the severe limitation as re-

¹³⁰Chevenard, *Comptes Rendus*, 1919, 169, pp. 712 and 1922, 175, p. 486.

¹³¹Dickenson, *Journal*, Iron and Steel Institute, 1922, 106, p. 103, and *Engineering*, 1922, 114, p. 326.

¹³²Lea, *Proceedings*, Institute of Mechanical Engineers, Vol. II, 1924, p. 1053.

¹³³Tapsell and Bradley, *Engineering*, Vol. 120, 1925, p. 614, *et seq.*

¹³⁴Brown, *Journal*, Institute of Metals, 1925, p. 21, and *Engineering*, Vol. 120, 1925, p. 461.

¹³⁵Jasper, *Proceedings*, American Society for Testing Materials, Vol. 25 (part 2), 1925, p. 27.

¹³⁶A. E. White, "Properties of Iron and Steel at High Temperatures," *TRANSACTIONS*, American Society for Steel Treating, Vol. 2, 1920, p. 521, and *Mechanical Engineering*, Vol. 49, 1927, p. 1093.

¹³⁷Kanter and Spring, *Proceedings*, American Society for Testing Materials, June, 1928.

¹³⁸French, Cross and Peterson, Bureau of Standards Technical paper No. 362.

¹³⁹W. H. Hatfield, *Journal*, Iron and Steel Institute, Vol. I, 1928.

guards sensitivity of measurement. In our own researches we work to a direct observation of $1/40,000$ of an inch, others claim to be working to a direct observation of $1/1,000,000$ of an inch, but it will be quite clear that deformation may, under certain conditions, be proceeding at a rate which is so slow as not to be observed, even with the most delicate measurement, except over the longest periods of time. This fact gives an opening for the expression of the abstract idea that "any metal will be deformed under any stress, given a long enough period of time." It is one of those propositions difficult to establish, and equally difficult to disprove. Nevertheless, on general grounds, as indicated above, the author holds the contrary view that steels have elastic ranges over the range of temperature in which the engineering world is interested, and, further, that it is our business to know what those ranges are. To leave theoretical discussion, the observation may be made that the point at issue is whether we can, or cannot, give the engineer a factor of safety as regards the time effect in the expectation of life of the part concerned. The answer is in the affirmative. From this point of view, it is interesting to consider the results of our present methods of attack.

In Britain there is a completely free exchange of ideas and a general collaboration between those responsible for design, and those engaged in the production of the material, and the subject is being followed from point to point with the greatest interest, in the hopes of immediate practical solution. The author has heard the view expressed by turbine engineers, that they would be in the position to design adequately with resultant suitable factors of safety, if they were in possession of the data concerning the stresses below which the rate of creep would not exceed 0.000001 per inch per hour.

An extremely valuable summing up of the present position as regards the properties of steels for use in connection with superheated steam, has recently been given by R. G. C. Batson,¹⁴⁰ and he gives typical data concerning the limiting creep stress, as disclosed in Tables XX and XXI.

These data relate to mild carbon steels, and Batson states that even by increasing the strength of the steel by increasing the carbon content, a limiting creep stress exceeding 11200 pounds per

¹⁴⁰R. G. C. Batson, Institution of Civil Engineers, Engineering Conference, June, 1928.

square inch (5 tons per square inch) cannot be obtained, even with a carbon content of 0.51 per cent at 932 degrees Fahr. (500 degrees Cent.).

The limiting creep stresses stated in this paper are the result of work at the National Physical Laboratory.¹⁴¹

The limiting creep stress as determined at the National Physical Laboratory, is the stress above which there is a steady continuous creep of a measurable rate within the accuracy of their

Table XX
Steel for Boiler and Superheater Tubes

		0.10 per cent Carbon Steel						0.17 per cent Carbon Steel					
Temperature		Limit of Proportionality		Ultimate Tensile Stress		Limiting Creep Stress		Limit of Proportionality		Ultimate Tensile Stress		Limiting Creep Stress	
Degrees Cent.	Degrees Fahr.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.
400	752	..	..	..	..	..	..	6.5	14560	29.0	65000	13.4	30020
450	842	..	..	..	..	..	..	5.5	12320	24.5	54900	8.5	19040
480	896	4.0	8960	17.0	38100	5.5	12320	5.0	11200	21.5	48200	6.0	13440
500	932	3.3	7390	14.9	33380	3.5	7840	4.3	10750	19.4	43500	4.8	10750
525	977	2.9	6500	13.7	30690	2.0	4480	4.4	9860	17.0	38100	3.5	7840
550	1022	2.5	5600	12.1	27100	1.3	2910	4.0	8960	15.0	33600	2.4	5380
570	1058	2.2	4930	10.5	23520	1.0	2240	3.5	7840	13.0	29100	2.0	4480
600	1112	1.9	4260	8.4	18820	0.6	1340	2.8	6270	11.0	24600	1.2	2690

measurements. Test pieces are loaded for several months at different values of stress, and the rate of creep to which the pieces settle down is determined. From these rates of creep a curve is drawn from which a close estimate is made of the limiting creep stresses. In a recent discussion, the author elicited the fact from Mr. Tapsell, who had been conducting this research, that four to five months were required to obtain a satisfactory value of limiting creep stress at one temperature. Quite clearly, therefore, researches having as their object the improvement of steel as regards an increase in the limiting creep stress, are severely handicapped owing to the great time required for discriminating examination of steels of varying composition and diverse heat treatments. This unsatisfactory position has been dealt with in the Brown-Firth research laboratories by arbitrarily deciding the conditions of the standardized test likely to be helpful in this direction. The meth-

¹⁴¹Special Report No. 2 of the Department of Scientific and Industrial Research, Engineering Research, National Physics Laboratory, London, 1927.

Table XXI
0.23 Per Cent Carbon Steel for Superheater and Steam Drums

Temperature		Limit of Proportionality		Ultimate Tensile Stress		Limiting Creep Stress	
Deg. Cent.	Deg. Fahr.	tons/sq. in.	lbs./sq. in.	tons/sq. in.	lbs./sq. in.	tons/sq. in.	lbs./sq. in.
400	752	6.3	14110	26.0	58240	13.5	30240
470	878	5.3	11870	18.5	41440	7.0	15680
530	986	4.0	9000	16.4	36740	4.0	8960
(approx.)							

od adopted consists in discovering, by static loading, the stress within which, at the temperature, stability of dimensions is attained within a period of 24 hours for a further period of 48 hours with an extension not exceeding the elastic deformation by 0.5 per cent on the gage length, with limitation as regards measurement for permanence of dimensions to 0.01 per cent of the gage length. This value the author has named the time-yield. It will be seen that a single value for a given temperature is obtained by this method in three days, and the matter is, therefore, brought, in point of time, within limits which permit a large number of tests being made in a reasonable period.

It is interesting to consider the value of the results so obtained in relation to the limiting creep stress values given by Batson as a result of the standard creep test determination. If we take mild carbon steel of about 0.25 per cent carbon, having a maximum stress value at ordinary temperatures of 72000 to 74000 pounds per square inch. (32 to 33 tons per square inch), at 752 degrees Fahr. (400 degrees Cent.) the limiting creep stress value obtained is given at 30,240 pounds (13.5 tons) per square inch, whereas at this temperature the time-yield determination, as just discussed, gives a value closely approaching 26880 pounds (12 tons) per square inch. At 932 degrees Fahr. (500 degrees Cent.) the limiting creep stress may be safely deduced as being about 13400 pounds per square inch (6 tons per square inch) and the time-yield value obtained will be in the neighborhood of this figure. If one considers the steel at 1112 degrees Fahr. (600 degrees Cent.), it will be seen that the limiting creep stress is about 3360 pounds

per square inch (1.5 tons per square inch), and the time-yield value obtained is slightly under this figure. It thus becomes clear that if a comparison be made between the values obtained under the ordinary tensile test at elevated temperatures (see Table XXIII) the time-yield values are very materially below the yield values under the ordinary tensile test, and that they do, indeed, practically give a value which has more bearing upon design than the limiting creep figures obtained from the creep test method of research, since the latter does not base the final figures on initial extension.

The Table XXII is given in pounds per square inch (in tons per square inch) for a 0.27 per cent carbon steel, the limiting creep stress, as determined by the National Physical Laboratory, the time-yield as determined by the Brown-Firth research laboratories, together with the limit of proportionality, the ordinary yield point and the maximum stress as regards the range of temperature extending from 572 to 1112 degrees Fahr. (300 to 600 degrees Cent.). It should also be remembered that the creep limit gives no indication of initial deformation, which is of great importance to the designer, whereas the time-yield does give such information.

As indicating the effect of various loads on the manner of deformation at a given temperature, Fig. 17 is of interest. In that graph will be found portrayed the resultant curves due to loading 0.40 per cent carbon steel at 752 degrees Fahr. (400 degrees Cent.) under 10, 12, 13, 14 and 15.3 tons per square inch respectively. This graph clearly and definitely demonstrates that the time-yield, as herein suggested and determined, is a value which

Table XXII

Temperature		Limit of Proportionality		Yield Point		Maximum Stress		Time-Yield		Creep Limit	
Deg. Cent.	Deg. Fahr.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.
300	572	13.2	29600	18.0	40300	40.5	90700	about 16.0	30800	29.0	65000
400	752	9.4	21060	15.8	35400	36.2	81100	about 11.0/12.0	26900	13.8	30900
500	932	6.0	13440	13.7	30700	26.1	58500	about 6.0	13400	5.0/6.0	11200/13400
600	1112	3.5	7840	...	.....	13.7	30700	1.0/1.5	2240/3360	1.5 about	3360

Table XXIII
Tensile Tests on Carbon Steels at Elevated Temperatures

0.14 Per Cent Carbon Steel								
Temperature, Deg. Cent.	Temperature, Deg. Fahr.	Limit of Proportionality, tons per square inch	pounds per square inch	Yield Point, tons per square inch	pounds per square inch	Maximum Stress, tons per square inch	pounds per square inch	Elongation, per cent
15	59	17.8	39870	17.9	40090	27.2	60930	38.0
100	212	15.8	35390	17.7	39650	28.1	63940	34.5
200	392	14.9	33380	17.3	38750	30.0	67200	27.0
300	572	13.1	29340	15.5	34720	32.5	72800	23.2
400	752	7.8	17470	12.9	28900	25.2	56450	37.6
500	932	.....	.....	.....	.....	20.0	44800	38.0
600	1112	.....	.....	.....	.....	12.5	28000	48.0
700	1292	.....	.....	.....	.....	6.8	15230	56.0
800	1472	.....	.....	.....	.....	4.0	8960	65.0
900	1652	.....	.....	.....	.....	2.0	4480	75.0
1000	1832	.....	.....	.....	.....	.....	.....	.....
0.30 Per Cent Carbon Steel								
15	59	21.6	48380	22.2	53720	36.6	81980	26.6
100	212	18.6	41660	18.75	42000	33.7	75490	23.2
200	392	16.4	36740	20.7	46370	40.7	91170	22.4
300	572	14.3	32030	19.4	43460	43.55	91550	18.7
400	752	10.1	22620	19.4	43460	40.7	91170	28.0
500	932	.....	.....	15.0	33600	28.6	64060	30.4
600	1112	.....	.....	.....	.....	15.5	34720	51.0
700	1292	.....	.....	.....	.....	8.07	18080	43.8
800	1472	.....	.....	.....	.....	5.47	12250	60.7
900	1652	.....	.....	.....	.....	3.75	8400	68.0
1000	1832	.....	.....	.....	.....	2.65	5930	78.0
0.42 Per Cent Carbon Steel								
15	59	25.0	56000	26.6	59580	41.0	91840	22.4
100	212	20.5	45920	23.2	55960	40.08	89780	23.2
200	392	20.0	44800	25.0	56000	43.88	97840	17.6
300	572	20.8	46590	25.87	56950	49.67	111260	13.6
400	752	15.5	34720	25.2	56450	42.0	914080	28.8
500	932	10.0	22400	20.7	46370	53.5	75040	25.1
600	1112	.....	.....	.....	.....	21.0	47040	32.0
700	1292	.....	.....	.....	.....	10.1	22620	44.8
800	1472	.....	.....	.....	.....	5.95	13330	66.4
900	1652	.....	.....	.....	.....	4.17	9340	56.7
1000	1832	.....	.....	.....	.....	2.42	5420	80.0

can undoubtedly form a safe basis for design; particularly having in mind that the period over which observation is made, taken in conjunction with the degree of accuracy of measurement, discloses movements of a less order than one-millionth of an inch per inch per hour.

A good wrought iron is the commercial approximation to pure iron, and it is of interest to record that the time-yield values are very materially lower, as would be expected, than in the case of mild steel. A value of 14780 pounds per square inch (6.6 tons

per square inch) is obtained at 752 degrees Fahr. (400 degrees Cent.), while at 932 degrees Fahr. (500 degrees Cent.) this value is lowered to 8960 pounds per square inch (4.0 tons per square inch).

When considering the hardened and tempered alloy steels, one finds the values disappointing. For instance, 3 per cent nickel steel, which has a time-yield of 50400 pounds per square inch (22.5

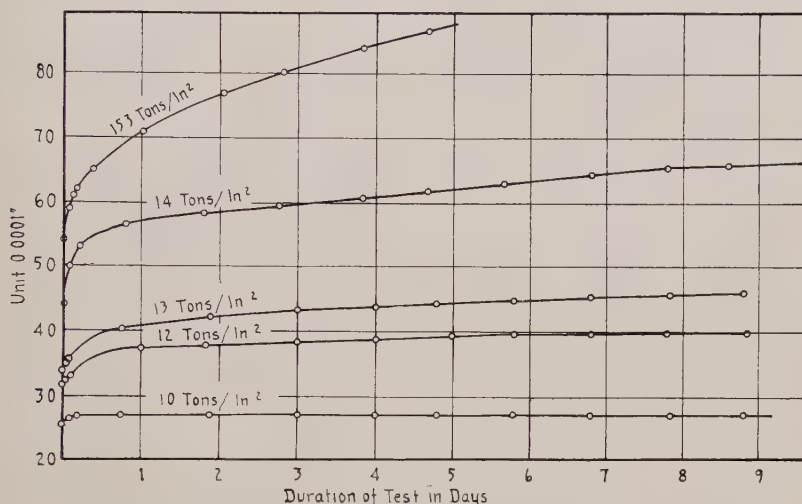


Fig. 17—Curves Showing the Effect of Various Loads on the Manner of Deformation at a Given Temperature.

tons) at 752 degrees Fahr. (400 degrees Cent.), discloses a value so low as 19040 pounds per square inch (8.5 tons) at 932 degrees Fahr. (500 degrees Cent.): while a 60-65-ton hardened and tempered nickel-chromium-molybdenum steel at 932 degrees Fahr. (500 degrees Cent.) gives a value of 17900 to 20100 pounds per square inch (8.0 to 9.0 tons per square inch), which falls to 4480 pounds per square inch (2 tons per square inch) at 1112 degrees Fahr. (600 degrees Cent.). Tables XXIV and XXV are included as indicating the values of the ordinary tensile test as modified by increasing temperature, as regards the typical special steels. The nickel-chromium-tungsten steel given in Table XXV belongs to the new type of heat resisting steel which is now being developed, and it is of great interest to record that greatly increased values as regards time-yield determinations are obtained. This partic-

Table XXIV

Tensile Tests on Hardened and Tempered High-Tensile Alloy Steels at Elevated Temperatures

Heat Treated 3 Per Cent Ni Steel									
Temperature, Deg. Cent.	Temperature, Deg. Fahr.	Limit of Proportionality, tons per square inch	pounds per square inch	Yield Point, tons per square inch	pounds per square inch	Maximum Stress, tons per square inch	pounds per square inch	Elongation, per cent	Reduction of Area, per cent
15	59	29.3	65630	32.2	72130	50.7	113570	23.3	59.2
100	212	23.0	62720	34.4	77060	48.5	108640	25.0	56.4
200	392	26.3	58910	34.0	76160	48.4	108420	25.4	56.0
300	572	25.2	56450	33.6	75260	47.7	106850	21.0	57.0
400	752	22.7	50850	33.3	74590	46.95	105170	21.6	50.4
500	932	.....	.....	22.4	50180	29.1	65180	28.0	79.4
600	1112	.....	.....	11.75	26320	18.67	41820	40.0	89.8
700	1292	.....	.....	.....	.....	11.5	25760	48.0	96.0
800	1472	.....	.....	.....	.....	6.53	14630	71.2	93.0
900	1652	.....	.....	.....	.....	4.025	9020	56.0	83.0
1000	1832	.....	.....	.....	.....	2.45	5490	72.6	99.0
Heat Treated Cr-Va Steel									
15	59	53.53	119910	55.55	124430	61.0	136640	21.6	61.5
100	212	53.9	120740	57.5	128800	62.6	140220	20.0	63.0
200	392	49.5	110880	53.12	118980	59.6	133500	15.6	61.5
300	572	43.5	97440	49.2	110210	55.6	124540	20.0	59.0
400	752	36.1	80860	46.6	104380	56.3	126110	15.6	61.5
500	932	15.5	34720	27.0	60480	32.6	73020	26.4	74.4
600	1112	.....	.....	.....	.....	24.8	55550	30.4	87.0
700	1292	.....	.....	.....	.....	11.6	25980	52.0	92.0
800	1472	.....	.....	.....	.....	6.7	15010	68.0	95.0
900	1652	.....	.....	.....	.....	4.7	10530	81.5	96.0
1000	1832	.....	.....	.....	.....	3.1	6940	73.5	97.0
Heat Treated Ni-Cr Steel									
15	59	46.5	104160	48.8	109310	57.8	129470	22.6	63.6
100	212	34.4	77060	47.5	106400	56.4	126330	23.2	67.7
200	392	32.6	73020	45.6	102140	54.85	122860	20.0	64.6
300	572	37.0	82880	48.5	108640	55.28	123830	20.0	50.2
400	752	30.4	68100	46.89	105340	55.41	124120	17.6	44.0
500	932	22.0	49280	38.97	87290	44.91	100600	21.6	66.5
600	1112	.....	.....	.....	.....	23.62	52900	32.0	88.0
700	1292	.....	.....	.....	.....	12.31	27570	42.4	90.0
800	1472	.....	.....	.....	.....	5.6	12540	74.3	92.0
900	1652	.....	.....	.....	.....	4.53	10150	52.0	84.6
1000	1832	.....	.....	.....	.....	2.97	6650	82.5	99.0

ular steel has a time-yield of 40300 pounds per square inch (18.0 tons per square inch) at 932 degrees Fahr. (500 degrees Cent.); at 1112 degrees Fahr. (600 degrees Cent.) a value so high as 28,200 pounds per square inch (12.6 tons per square inch) is maintained. The author considers that sufficient data have been quoted concerning the time-temperature effect as regards ordinary steels, and he cannot too strongly recommend a study of the time-yield upon the lines indicated. In the Laboratories under his charge are

Table XXV

Tensile Tests on a Heat Treated Chromium Steel and Silico-chromium and Nickel-chromium-tungsten Steels at Elevated Temperatures

Heat Treated 14 Per Cent Cr Steel									
Temperature, Deg. Cent.	Temperature, Deg. Fahr.	Limit of Proportionality, tons per square inch	pounds per square inch	Yield Point, tons per square inch	pounds per square inch	Maximum Stress, tons per square inch	pounds per square inch	Elongation, per cent	Reduction of Area, per cent
15	59	28.6	64060	35.7	79970	48.5	108640	28.0	62.5
100	212	28.0	62720	35.8	80190	45.9	102820	24.8	65.4
200	392	28.5	63840	35.4	79300	43.5	97440	23.2	65.4
300	572	26.1	58460	33.9	75940	41.3	92510	21.0	64.0
400	752	23.4	52420	31.2	69890	37.8	84670	20.8	62.0
500	932	.....	.....	.....	.....	32.7	73250	16.8	56.6
600	1112	.....	.....	.....	.....	18.8	42110	20.5	67.0
700	1292	.....	.....	.....	.....	12.1	27100	36.8	85.4
800	1472	.....	.....	.....	.....	5.04	11290	45.6	91.5
900	1652	.....	.....	.....	.....	.....	.....	.....	.....
1000	1832	.....	.....	.....	.....	.....	.....	.....	.....
Si-Cr Steel									
15	59	48.5	108640	59.0	132160	68.0	152320	20.0	49.0
100	212	.....	.....	58.5	131040	68.5	153440	21.6	50.0
200	392	.....	.....	50.2	112450	63.0	141120	21.6	52.0
300	572	.....	.....	45.9	102820	58.2	130370	20.8	50.0
400	752	.....	.....	45.0	100800	57.0	127680	22.4	51.0
500	932	.....	.....	39.0	87360	45.3	101470	28.0	54.5
600	1112	.....	.....	.....	.....	24.5	54880	47.0	87.0
700	1292	.....	.....	.....	.....	10.08	22580	61.5	95.0
800	1472	.....	.....	.....	.....	4.87	10910	60.3	97.0
900	1652	.....	.....	.....	.....	2.82	6320	88.0	97.0
1000	1832	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Cr-W Steel									
15	59	23.2	51970	36.0	80640	63.0	141120	23.5	24.0
100	212	.....	.....	37.5	84000	53.5	119840	24.8	33.2
200	392	.....	.....	35.3	79070	49.4	110660	20.8	28.6
300	572	.....	.....	32.6	73020	43.4	97220	22.5	32.8
400	752	.....	.....	29.4	65860	42.7	95650	20.8	32.8
500	932	.....	.....	26.0	58240	39.5	88480	23.5	46.0
600	1112	.....	.....	.....	.....	34.1	76380	25.0	55.4
700	1292	.....	.....	.....	.....	28.2	63170	28.0	61.0
800	1472	.....	.....	.....	.....	17.2	38530	40.0	74.0
900	1652	.....	.....	.....	.....	12.0	26880	51.0	79.0
1000	1832	.....	.....	.....	.....	6.02	13450	70.0	81.0

a number of machines at work, and data are being steadily accumulated which cannot fail to be of great value.

The Influence of Temperature on the Fatigue Properties of Steels

Comparatively little work has been done on the fatigue properties of materials at elevated temperatures, and, as yet, no correlation has been achieved as regards the astonishing indications as to fatigue values at high temperatures, and the values as regards

static stress required to produce plastic deformation. The first appears to be that by Professor F. C. Lea and H. P. Budgeon,¹⁴² who found that the range of stress for zero mean stress, varied only slightly until comparatively high temperatures were reached. Thus a 0.14 per cent carbon steel had a fatigue range of ± 33600 pounds per square inch (± 15 tons per square inch) at 60 degrees Fahr. (15 degrees Cent.), the same at 392 degrees Fahr. (200 degrees Cent.), beyond which the range increased slightly to a maximum of ± 40300 pounds per square inch (± 18 tons per square inch) at nearly 750 degrees Fahr. (400 degrees Cent.). At still higher temperatures the fatigue range began to fall. For a nickel-chromium steel (3.25 per cent nickel, 0.6 per cent chromium, 0.35 per cent carbon) the range fell slightly from ± 58200 pounds per square inch (± 26 tons per square inch) at 60 degrees Fahr. (15 degrees Cent.) to ± 44800 pounds per square inch (± 20 tons per square inch) at 572 degrees Fahr. (300 degrees Cent.), then rose to a maximum of ± 51500 pounds per square inch (± 23 tons per square inch) at 752 degrees Fahr. (400 degrees Cent.) after which it fell slowly to ± 38100 pounds per square inch (± 17 tons per square inch) at 1400 degrees Fahr. (760 degrees Cent.). Similar results with slightly displaced maxima and minima, were obtained on a nickel-chromium steel containing 0.3 per cent carbon, 3.6 per cent nickel and 0.6 per cent chromium. The fatigue range above 752 degrees Fahr. (400 degrees Cent.) may be greater than the limiting creep stress at the same temperature. Thus it would appear to be possible, according to the data presented, to run specimens of the 0.14 per cent carbon steel at 932 degrees Fahr. (500 degrees Cent.) with a range of stress of more than 29000 pounds per square inch (13 tons per square inch), and a mean stress of 33600 pounds per square inch (15 tons per square inch), although the limiting creep stress at this temperature was only 8960 pounds per square inch (4 tons per square inch). The speed of reversal was 2000 per minute.

Moore and Jasper¹⁴³ have carried out fatigue tests on some metals at high temperatures under conditions of zero mean stress. Their results are collected in Table XXVI. The speed of revolution in the above tests was 1500 revolutions per minute.

¹⁴²F. C. Lea and H. P. Budgen, *Engineering*, October 3, 1924, p. 500.

¹⁴³Moore and Jasper, *University of Illinois Bulletin*, No. 152, 1925.

Table XXVII
Fatigue Ranges Pounds Per Square Inch

Temp. of Test	Armco Iron	0.17% Carbon Steel				Carbon Steels		
						0.24%	0.51%	0.53%
Air	±2600 ±11.9	±28000 ±12.5	44300 +22 to 0	66100 +29.5 to	32500 +14.5	±29800 ±13.3	±32900 ±14.7	±27300 ±12.2
100° C. (212° F.)	±24000 ±10.7	±27500 ±12.3	47000 +21 to 0	65000 +29 to	29100 +13	±27500 ±12.3	±31000 ±13.85	±28900 ±12.9
200° C. (392° F.)	±25500 ±11.4	±27500 ±12.3	51500 +23 to 0	76200 +34 to	26900 +12	±27300 ±12.3	±31100 ±13.9	.....
300° C. (572° F.)	±33400 ±14.9	±35800 ±16.0	67200 +30 to 0	85100 +38 to	49300 +22	±35800 ±16.0	±43200 ±19.3	±29100 ±13.0
400° C. (752° F.)	±28900 ±12.9	±37600 ±16.8	58200 +26 to 0	67200 +30 to	40300 +18	±38100 ±17.0	±43000 ±19.2	.....
500° C. (932° F.)	±12300 ±5.5	±26200 ±11.7	38100 +17 to 0	44800 +20 to	17900 + 8	±29100 ±13.0	±32000 ±14.3	±19500 ± 8.7
600° C. (1112° F.)	...	±15200 ± 6.8	.....	.....		±16350 ± 7.3	±16100 ± 7.2	±15700 ± 7.0

Results of the same nature have been obtained by Tapsell and Clenshaw¹⁴⁴ and by Tapsell.¹⁴⁵ Their results are collected in Table XXVII.

The speed of alternations in these tests was 2400 cycles per minute. The fatigue test results at high temperatures will undoubtedly be affected by the speed of revolution, but no data appear to have been obtained at present.

Influence of Temperature on the Behavior of Steels Under the Impact Test

The notched-bar impact test is much used and the question naturally arises as to how such values are affected by higher temperatures. Dealing with the matter as regards the range including the higher contemplated steam temperatures, it is agreed by experimentalists, that a material of high notched-bar impact value at normal temperature, generally retains a sufficiently satisfactory value through the range of temperature under consideration, while steels giving a low value at normal temperatures almost invariably give much increased values at the higher temperatures.

It has long been understood that steels pass through a range

¹⁴⁴Tapsell and Clenshaw, "Properties of Materials at High Temperatures," Department of Scientific and Industrial Research, Parts I, II and III, 1927 and 1928.

¹⁴⁵Tapsell, *Journal, Iron and Steel Institute*, May, 1928.

of temperature in which they are considered to possess the characteristic of blue brittleness.¹⁴⁶ The first systematic investigation of the subject appears to be that of Charpy,¹⁴⁷ who examined three carbon steels, a 1 per cent nickel steel, and a nickel-chromium steel. He found that the carbon steels all showed minimum brittleness (maximum toughness), in the neighborhood of 210 to 400 degrees Fahr. (100 to 200 degrees Cent.) and maximum brittleness between 750 to 930 degrees Fahr. (400 to 500 degrees Cent.). He recorded that only small variations occurred in the impact values of the two alloy steels between 176 and 1112 degrees Fahr. (80 and 600 degrees Cent.). Guillet and Revillon,¹⁴⁸ carried out impact tests on ordinary and special steels at high temperatures, and also found that for ordinary steels there was maximum resilience between 230 and 320 degrees Fahr. (110 and 160 degrees Cent.), and a minimum between 750 and 840 degrees Fahr. (400 and 450 degrees Cent.). Martensitic steels gradually increased in resistance to impact up to 986 degrees Fahr. (530 degrees Cent.), but appeared to pass through a maximum at about 300 to 340 degrees Fahr. (150 to 170 degrees Cent.). Austenitic steel gradually decreased in resistance to notched-bar impact as the temperature rose. Goerens and Hartel¹⁴⁹ found that a dead mild steel had low resilience at temperatures under normal. The impact value increased with temperature up to room temperatures and then fell to a minimum at 932 degrees Fahr. (500 degrees Cent.) reaching a well defined maximum at 1112 degrees Fahr. (600 degrees Cent.), after which it fell rapidly. Langenberg¹⁵⁰ carried out an extended investigation on the notch-bar impact test on materials at low and elevated temperatures. He found in all cases, that the resistance to impact increased with rise of temperature up to a maximum, after which the energy absorbed falls with further increase of temperature. In some cases there was a falling off of the resistance in the range 200 to 300 degrees Fahr. (93 to 150 degrees Cent.), which he suggests is due to the phenomenon of "blue-brittleness".

¹⁴⁶Howe, "The Metallurgy of Steel," 1891.

¹⁴⁷Charpy, *Bulletin, Societe des Ingenieurs Civils de France*, 1906, p. 563.

¹⁴⁸Guillet and Revillon, *Revue de Metallurgie*, Vol. 6, 1909, p. 918.

¹⁴⁹Goerens and Hartel, *Zeitschrift für Anorganische und Allgemeine Chemie*, Vol. 81, 1913, p. 130.

¹⁵⁰F. C. Langenberg, Carnegie Scholarship Memoirs, Vol. XII, 1923, and "Behaviour of Metals Under Normal and Sub-Normal Temperatures," a paper presented before the Eastern Sectional Meeting of the American Society for Steel Treating, June 14 and 15, 1923.

Greaves and Jones¹⁵¹ describe an investigation into the effect of temperature on the notched bar test. Two maxima were obtained in all cases except that of stainless steel. Using standard B. E. S. A. test pieces, the first maximum occurs at different temperatures between 0 and 480 degrees Fahr. (— 20 and 250 degrees Cent.) for different materials, the temperature at which the minimum impact figure is reached varies between 932 degrees Fahr. (500 degrees Cent.) for Armco iron and 1202 degrees Fahr. (650 degrees Cent.) for some heat treated alloy steels, and the second maximum occurs between 1200 and 1470 degrees Fahr. (650 and 800 degrees Cent.). The positions of the maxima and minima are altered considerably when the size of the notch is varied. For a fairly wide range of radius of the notch, the curve does not markedly change its form, but a change of radius from 10 to 200 millimeters causes a distinct alteration in the curve. The temperature of the first maximum for Armco iron is lowered from 392 degrees Fahr. (200 degrees Cent.) with notch sizes up to 1 millimeter, to — 112 degrees Fahr. (— 80 degrees Cent.) with an unnotched test piece. Cold work tends to raise the temperature at which the first maximum occurs. Evidence is given which attempts to connect the phenomenon of "blue-brittleness" with the minimum. Stainless steel showed a rapid rise in impact resistance up to 212 degrees Fahr. (100 degrees Cent.) and then increased very gradually up to 1832 degrees Fahr. (1000 degrees Cent.): no well defined maxima or minima were observed.

Greaves and Jones's paper also contains an excellent bibliography of the subject. It would appear, therefore, that apart from the general trend of one or two maxima, the curve showing impact variations with temperatures is so dependent on previous treatment, size, and type of notch, that each material and treatment should be examined separately. No complete generalization as to effect of composition can be made from published results.

Tables XXVIII and XXIX give some conception to the magnitude of the changes which take place in the notch bar impact figures at elevated temperatures. Langenberg—size of test piece $30 \times 30 \times 155$ millimeters, notch 2 millimeters radius, 15 millimeter depth.

Greaves and Jones—size of test piece $10 \times 10 \times 60$ milli-

¹⁵¹Greaves and Jones, *Journal*, Iron and Steel Institute, September, 1925.

Table XXVIII

Material	Condition	Room temp., ft.-lbs.	1st Max.		Impact		Figures		2nd Max.	
			Temp., deg. Cent.	Temp., deg. Fahr.	Temp., deg. Cent.	Temp., deg. Fahr.	Min.	Impact, ft.-lbs.	Temp., deg. Cent.	Temp., deg. Fahr.
2% Ni, 1% Cr, 0.2% C	Annealed	475	260	500	725	540	1000	410	...	...
	Hardened and temp. 260° C.	600	110	230	803	400	750	450	...	...
3.3% Ni, 0.3% C	Annealed	159	260	500	469	540	1000	217	...	...
	Hardened and temp. 600° C.	313	260	500	604	540	1000	311	...	...
1.9% Ni, 1% Cr, 0.36% C	Annealed	198	400	750	478	540	1000	289	...	...
	Hardened and temp. 600° C.	307	260	500	657	540	1000	396	...	...
0.9% Cr, 0.36% C	Annealed	31	180	356	401	540	195	...	...	...
	Hardened and temp. 450° C.	430	80	176	865	108	225	599	260	500 867
0.83% C	Annealed	24	400	750	181	...	...	...	...	...
	Hardened and temp.	65	120	250	235	177	350	170	260	500 229
0.18% C	Annealed	61	120	250	868	540	1000	412	...	...
	Hardened and temp. 260° C.	893	108	225	1067	540	1000	434	...	...

meters, 45 degree V-notch 0.25 millimeter root radius, 2 millimeters depth.

Corrosion at the Higher Steam Temperatures

The question as to how far internal surfaces in contact with steam at the higher temperatures and pressures will become more susceptible to corrosion, has been raised, notably by Stuger and Bohnenblust,¹⁵² and the author is of the opinion that corrosion must be indeed accelerated under such conditions. This matter must be thoroughly borne in mind and every step taken, particularly in eliminating oxygen from the feed. Experiments conducted in the author's laboratories, on several steels at 1000 degrees Fahr. (540 degrees Cent.), have shown definite attack over so short a period as 6 hours, in the case of ordinary steel when the steam was formed from water containing 5 cubic centimeters of oxygen per litre. Examples of the rustless and other steels were tested at the same time, and the results were as follows, see Table XXX, the figures being given as gain in weight in milligrams per square centimeter of surface.

¹⁵²Stuger and Bohnenblust, Brown Boveri, November, 1927.

Table XXIX

Material	Condition	Room temp., kgm.	1st Max.				Impact Figures Min.				2nd Max.			
			Temp., Deg. Cent.	Temp., Deg. Fahr.	Impact, kgm.	Temp., Deg. Cent.	Temp., Deg. Fahr.	Impact, kgm.	Temp., Deg. Cent.	Temp., Deg. Fahr.	Impact, kgm.	Temp., Deg. Cent.	Temp., Deg. Fahr.	Impact, kgm.
Swedish Bar Iron	As rolled	16 & 4.5	15	60	16	540	1000	5	700	1290	10			
Armco Iron A	As rolled	5	200	392	12	500	930	4	800	1470	5			
Armco Iron B	As rolled	1	150	300	5	500	930	2.5	750	1380	4			
0.18% Carbon	As rolled	15.5	15	60	15.5	600	1110	5	700	1290	21			
0.13% Carbon	As rolled	2	100	212	3	600	1110	2	800	1470	5			
0.13% Carbon	Annealed	1.5	100	212	3	600	1110	2	800	1470	5			
0.13% Carbon	Water quenched	2.8	100	212	3	600	1110	1.5	800	1470	5			
	1652° Fahr.													
	Normalized	1.5	200	392	6	550	1020	2.5	750	1380	19			
0.39% Carbon	Hardened and temp.	1.5	150	300	7.5	550	1020	3	750	1380	19			
	1200° Fahr.													
	Normalized	1.0	200	392	3.5	550	1020	2	870	1600	11.5			
0.45% Carbon	Hardened and temp.	2.0	150	300	11.0	550	1020	3.5	690	1270	25.2			
	1200° Fahr.													
	Hardened and temp.	5.5	250	482	6.5	600	1110	3	750	1380	15			
	1200° Fahr.													
3.77% Ni, 0.35% Carbon	Annealed	2.5	250	482	5.5	550	1020	2.5	750	1380	13.5			
3.77% Ni, 0.35% Carbon	Annealed	1.5	150	300	3	600	1110	2	800	1470	12.5			
3.72% Ni, 0.92% Cr, 0.23% Carbon	O. H. and temp.	5.5	15	60	5.5	600	1110	3	800	1470	13			
3.72% Ni, 0.92% Cr, 0.23% Carbon	1200° F.													
3.72% Ni, 0.92% Cr, 0.23% Carbon	W. Q.													
	O. H. and temp.	1.0	300	572	4.5	600	1110	3	800	1470	13			
Cr, 0.23% Carbon	1200° F.													
3.72% Ni, 0.92% Cr, 0.23% Carbon	S. C. 1652° F.													
	S. C. 3 Rises to 10 at 392° Fahr. and then gradually to 13.5 at 1832° Fahr.													
Stainless steel	O. H. and temp.													
12.37% Cr, 0.43% Carbon	1292° F.													
	3 Rises to 7 at 212° Fahr. and then remains fairly constant up to 1290° Fahr., after which it rises to 13.5 at 1832° Fahr.													

Heat Resisting Steels

Heat resisting steels are essentially steels which will work in temperatures approximately ranging from 1100 to 1830 degrees

Table XXX

Material	Gain in Weight
0.25 per cent carbon steel	0.62
High tensile alloy steel	0.73
14 per cent chromium stainless steel	0.24
18 per cent chromium 8 per cent nickel, rustless steel	0.01

Fahr. (600 to 1000 degrees Cent.), with a much less scaling effect than occurs with ordinary ferrous materials. A number of interesting papers have been published dealing with the subject. Dickenson¹⁵³ studied the differential effect on several steels and alloys at various temperatures. McCormick¹⁵⁴ dealt with the effect of the furnace atmosphere in producing scale on steels of varying carbon content. There are several papers dealing essentially with valve steels; Aitchison¹⁵⁵ indicated the value of chromium steels, while Grard,¹⁵⁶ after an interesting description of various tests, claimed excellent characteristics for chromium-silicon steels. Mahoux¹⁵⁷ was responsible for an interesting metallurgical survey, and Henshaw¹⁵⁸ has made a review of the position to date. The latter author gave much valuable data concerning the composition and characteristics of heat-resisting steels in current use for meeting the onerous conditions imposed on aero-engine valves, and discussed the chromium, chromium-silicon, nickel-chromium, cobalt-chromium, and nickel-chromium-tungsten steels. The author has published two papers, one dealing with the resistance to scaling of such materials,¹⁵⁹ and the other dealing with the mechanical properties.¹⁶⁰

The subject, as regards the mechanical properties of the materials, can be well considered, and indeed can only, at the present time, be studied by arbitrarily selecting a temperature and obtaining the comparative results obtained under a standardized tensile test. As will be clear from the foregoing matter, however, in this section, in which the question of the effect of the manner of applying the load upon the nature of the deformation, has been discussed, only those investigators who have given attention to the subject can appreciate how difficult it is to present comparative data concerning the strength of steel at high temperatures. In

¹⁵³Dickenson, *Journal*, Iron and Steel Institute, No. II, 1922, p. 103.

¹⁵⁴G. C. McCormick, "Furnace Atmospheres and Their Relation to the Formation of Scale," *TRANSACTIONS*, American Society for Steel Treating, Vol. 2, 1922, p. 1006.

¹⁵⁵Aitchison, *Automobile Engineering*, Vol. IX, 1919, p. 401, and *Engineering*, Vol. CVIII, 1919, pp. 799-834.

¹⁵⁶Grard, *Comptes Rendus*, Vol. CIXXXI, 1925, p. 1143.

¹⁵⁷Mahoux, *Revue de Metallurgie, Memoires*, XXII, 1925, p. 39.

¹⁵⁸Henshaw, Paper read before the Royal Aeronautical Society, December 2, 1926.

¹⁵⁹W. H. Hatfield, *Journal*, Iron and Steel Institute, Vol. CXV, 1927.

¹⁶⁰W. H. Hatfield, *Journal*, Iron and Steel Institute, 1928.

Table XXXI
Tensile Tests at 15° and 800° C. (59° and 1472° F.)

Steel No.	Material	C	Mn	Si	S	P	Cr	Ni	Mo	V	Co	W	Al	Cu	Condition	Y. P., tons, and lbs., per sq. in.	M. S. tons, and lbs., per sq. in.	Elongation, %	R/A, %	15° C. (60° F.) (1472° F.)	800° C.	
1	Wrought Iron	0.09	0.08	0.10	....	....	....	....	....	....	....	....	....	....	As forged	13.78 30900	22.34 50000	29.0 48.43	2.03 53.5	58.0	R/A, %	
2	Mild Steel	0.14	0.56	0.02	0.048	0.04	....	....	....	....	....	....	....	....	Normalized	19.50 43700	27.2 60900	38.0 61.0	4.0 75.0	98.0	Elongation, %	
3	Steel 3%	0.34	0.60	0.29	0.021	0.012	....	3.28	....	....	....	....	....	....	O. H. 850° C.	32.2 72100	50.7 113600	23.3 59.2	5.37 52.0	82.2	Elongation, %	
4	Nickel 3%	0.29	0.60	0.27	0.014	0.018	0.89	3.41	....	....	....	....	....	....	O. H. 850° C.	48.8 109300	57.8 129500	24.0 63.6	5.60 74.3	78.0	Elongation, %	
5	Ni-Cr	0.30	0.57	0.24	0.010	0.015	0.61	2.38	0.59	....	....	....	....	....	T. 850° C.	56.4 126300	63.7 142700	24.0 66.0	7.68 70.3	90.0	Elongation, %	
6	Cr-Va	0.43	0.59	0.22	0.039	0.034	1.14	0.32	... 0.18	....	....	....	....	....	O. H. 850° C.	50.9 114000	58.5 131000	18.7 62.0	6.70 88.0	95.0	Elongation, %	
7	Si-Cr	0.35	0.57	3.27	....	....	9.45	....	....	....	....	....	....	....	Annealed	52.0 116500	70.0 156800	13.0 20.5	6.05 86.5	99.0	Elongation, %	
8	Si-Cr Valve	0.57	0.42	4.07	....	....	8.5	....	....	....	....	....	....	....	O. H. 1075° C.	59.0 132200	68.0 152300	20.0 49.0	3.93 81.6	99.3	Elongation, %	
9	High-Speed	0.55	0.24	0.23			3.36		... 0.47		14.75				A. C.		47.45	21.6	38.7	8.7	43.0	Elongation, %
10	High-Speed	0.56	0.20	0.21			4.15		... 0.65		16.05				Annealed		50.0	22.0	38.5	8.0	51.0	Elongation, %
11	High-Speed	0.54	0.22	0.39	....	....	4.08	....	... 0.84	....	18.0	....	....	....	Annealed	28.3 63400	51.6 115600	16.6 27.5	10.5 42.4	68.5	Elongation, %	
12	High-Speed Super	0.58	0.12	0.41	....	....	3.90	....	7.91	0.99	5.41	0.36	....	....	Annealed	48.8 109300	57.1 127900	15.2 23.4	8.8 48.0	83.0	Elongation, %	

H. R. Steel = Heat-Resisting Steel. O. H. = Oil Hardened. T. = Tempered. A. C. = Air Cooled. A. H. = Air Hardened. W. Q. = Water Quenched.

H. R. Steel = Heat-Resisting Steel. O. H. = Oil Hardened. T. = Tempered. A. C. = Air Cooled. A. H. = Air Hardened. W. Q. = Water Quenched.

Table XXXI (Continued)
Tensile Tests at 15° and 800°C. (59° and 1472°F.)

Steel No.	Material	C	Mn	Si	S	P	Cu	Ni	Mo	V	Co	W	Al	Cu	Condition	Y, P, lbs., per sq. in.	M, S, lbs., per sq. in.	15° C. (60° F.)	Elongation, %	R/A, %	M, S, lbs., per sq. in.	800° C. (1472° F.)	Elongation, %	R/A, %
13	Cobalt-Chrome	1.51	0.23	0.44	.....	.....	13.22	1.08	...	...	5.17	.....	...	...	Softened	36.4	54.6	13.0	16.5	13.0	29120	.....	.....	.....
14	Valve less	0.07	0.10	0.10	.....	.....	14.92	.....	...	...	.....	.....	...	...	Fully tempered	81500	122300	40.0	74.26	77.6	89.8	.....	.....	.....
15	Iron	0.09	0.39	0.37	.....	.....	18.52	0.26	...	...	.....	.....	...	...	A. C. 900° C.	19.0	28.6	16.0	.....	3.0	81.5	.....	.....	.....
16	Experimental mental	0.16	0.30	1.31	.....	.....	14.04	.....	...	...	.....	.....	...	...	A. H. 950° C.	42600	64100	27.3	64.0	4.53	49.0	92.14	.....	.....
17	Experimental mental	0.31	0.30	1.16	.....	.....	13.17	0.32	...	...	.....	.....	...	...	T. 820° C.	.....	83800	.....	.....	.....	10150	76.8	83.3	.....
18	Experimental mental	0.36	0.12	0.26	.....	.....	14.66	0.30	...	...	.....	.....	...	...	A. H. 950° C.	69400	100800	22.0	45.0	6.04	45.6	91.5	.....	.....
19	Valve less	0.54	0.33	0.94	.....	.....	14.56	0.88	...	...	.....	.....	...	...	T. 600° C.	.....	129900	.....	.....	.....	13530	.....	.....	.....
20	Steel	0.23	0.18	0.10	.....	.....	Nil	12.23	...	...	.....	.....	...	...	As received	32.8	54.6	25.5	54.3	9.30	80.0	87.0	.....	.....
21	Experimental mental	0.27	0.93	0.79	.....	.....	0.05	25.7	...	...	.....	.....	...	...	A. C. 950° C.	83.0	99.0	12.0	31.0	5.75	43.2	40.5	.....	.....
22	Experimental mental	0.23	0.35	0.12	.....	.....	Nil	36.5	...	...	.....	.....	...	...	A. C. 950° C.	185900	221760	52.0	70.4	6.90	34.4	28.2	.....	.....
23	Experimental mental	0.09	0.25	0.03	.....	.....	Nil	11.91	...	...	.....	1.85	.....	...	A. C.	29300	89600	44.5	64.0	7.85	37.5	83.7	.....	.....
24	Experimental mental	0.11	0.34	0.21	.....	.....	14.84	10.16	...	...	.....	.....	...	...	1000° C.	64.6	71.7	12.5	32.0	7.2	37.0	84.0	.....	.....
															As rolled	144700	160600	52.0	68.1	10.17	46.4	44.0	.....	.....
																55100	101200	.....	.....	.....	22780	.....	.....	.....

H. R. Steel = Heat-Resisting Steel. O. H. = Oil Hardened. T. = Tempered. A. C. = Air Cooled. A. H. = Air Hardened. W. Q. = Water Quenched.

Table XXXI (Continued)
Tensile Tests at 15° and 800°C. (59° and 1472°F.)

Steel No.	Material	C	Mn	Si	S	P	Cr	Ni	Mo	V	Co	W	Al	Cu	Condition	15° C.				800° C. (1472° F.)			
																lbs., per sq. in.	M. S. tons, and	lbs., per sq. in.	Elongation, %	M. S. tons, and	Elongation, %	lbs., per sq. in.	R/A, %
25	Experimental	0.29	0.29	0.17	....	....	14.08	11.90	....	....	....	....	....	....	A. C.	18.2	42.8	12.65	30.4	28330	64.0	65.0	33.0
26	Experimental	0.41	0.46	1.10	....	....	13.94	9.84	....	3.15	....	....	....	....	1150° C.	40700	95900	40.7	37.0	28330	9.0	12.6	68.5
27	Experimental	0.34	0.33	1.18	....	....	13.80	8.44	1.44	....	....	....	1.06	....	1000° C.	54200	103900	54.2	37.0	29340	21.0	.....	....
28	Experimental	0.64	0.61	1.54	....	....	14.3	13.0	....	....	....	1.0	....	....	A. C.	48200	125400	48.2	68.0	32100	22.0	81.5	67.0
29	Experimental	0.55	0.73	1.45	....	....	13.10	12.78	....	....	....	2.3	....	2.58	1000° C.	79700	126300	79.7	65.3	28000	22.5	32.0	65.3
30	H. R. Steel	0.42	0.31	0.69	....	....	13.30	8.87	....	....	....	3.42	....	....	1000° C.	85100	126700	85.1	66.8	31360	7.5	.....	....
31	H. R. Steel	0.57	0.48	0.72	....	....	13.97	9.5	....	....	....	3.36	....	....	930° C.	78800	127200	78.8	66.8	50660	22.75	16.0	32.8
32	Experimental	0.76	0.60	0.76	....	....	12.10	9.38	....	....	....	3.07	....	....	As forged	40.1	62.9	29.0	33.0	50400	29.0	33.0	47.0
33	Experimental	0.61	0.67	0.4	....	....	14.94	10.36	....	1.91	5.94	....	....	....	A. C.	28.4	57.0	11.0	11.0	3450	15.4	54.0	71.2
34	Experimental	0.47	0.70	0.14	....	....	12.47	19.67	....	....	....	3.57	....	....	1000° C.	78800	116500	78.8	66.4	30580	13.65	33.6	66.4
35	Experimental	0.13	0.13	0.56	....	....	17.88	7.74	....	....	....	....	....	....	W. Q.	82400	102400	82.4	37.8	43250	19.30	18.4	37.8
36	Experimental	0.41	0.13	0.11	....	....	19.92	8.92	....	....	....	....	....	....	1200° C.	39200	106600	39.2	14.5	16750	55.0	39.17	14.5
37	Experimental	0.34	0.48	0.85	....	....	18.51	7.78	....	....	....	3.09	....	....	W. Q.	24.0	53.35	41.0	50.9	20000	8.93	27.8	67.0
38	H. R. Steel	0.38	0.68	1.21	....	....	18.72	9.74	....	....	....	3.27	....	....	A. C.	33.2	70.0	10.0	.....	47100	21.3	.....	....
39	Experimental	0.30	0.52	1.46	....	....	17.70	7.0	....	....	....	4.23	....	....	1000° C.	65400	113300	65.4	59.0	44800	27.5	28.9	59.0
	Water Quenched.														1300° C.	85100	131040	85.1	53.0	39870	37.5	52.0	53.0

H. R. Steel = Heat-Resisting Steel. O. H. = Oil Hardened. T. = Tempered. A. C. = Air Cooled. A. H. = Air Hardened. W. Q. = Water Quenched.

Table XXXI (Continued)
Tensile Tests at 15° and 800°C. (59° and 1472°F.)

Steel No.	Material	C	Mn	Si	P	Cu	Ni	Mo	V	Co	W	Al	Cu	Condition	15° C. (60° F.)				800° C			
															Y. P. tons, and lbs., per sq. in.	M. S. tons, and lbs., per sq. in.	Elongation, %	R/A, %	Y. P. tons, and lbs., per sq. in.	M. S. tons, and lbs., per sq. in.	Elongation, %	R/A, %
40	Experimental	0.58	0.36	4.0	....	....	15.54	8.14	....	....	....	....	....	A. C.	31.6	41.8	10.0	12.0	4.47	7.20	94.0	10010
41	Experimental	0.59	0.27	1.08	....	....	....	....	....	....	....	....	....	1000° C. Annealed	70800	93600	2.0	4.0	6.02	73.5	96.0	13480
42	Experimental	0.24	0.23	0.23	....	....	19.74	Nil	....	....	2.91	....	....	A. C.	18.8	39.6	48.0	67.0	13.2	33.5	38.4	29560
43	Experimental	0.25	0.42	3.24	....	....	19.4	0.25	....	....	3.25	....	....	A. C.	33.2	49.0	35.0	49.0	17.87	8.0	17.0	38910
44	Experimental	0.06	0.39	0.39	....	....	23.22	24.02	....	....	....	....	....	1050° C.	49.2	56.4	20.0	27.5	15.0	23.0	46.0	33600
45	Experimental	0.19	0.32	0.84	....	....	20.29	19.29	....	....	....	....	....	A. C.	24.2	47.7	35.5	50.0	19.58	24.0	51.0	43860
46	Experimental	0.25	0.96	2.20	....	....	23.85	17.21	....	....	....	....	....	As received	54900	106900	29.0	35.0	15.57	60.0	57.7	34880
47	H. R. Steel	0.29	1.16	1.81	....	....	14.95	24.82	....	....	2.86	....	....	1050° C.	30.0	48.6	26.0	31.0	16.55	40.0	49.8	37070
48	Experimental	0.48	0.85	0.19	....	....	24.75	16.39	....	....	3.85	....	....	A. C.	33.8	53.2	26.0	31.0	16.55	40.0	49.8	37070
49	Experimental	0.52	1.01	1.41	....	....	23.90	22.29	....	....	3.13	....	....	A. C.	75700	119200	31.0	51.0	13.7	45.5	54.8	30686
50	Experimental	0.35	1.36	0.21	....	....	10.9	35.15	....	....	....	....	....	As rolled	33.03	54.6	26.0	30.0	15.3	38.0	43.0	84270
51	Nichrome	0.06	0.89	0.71	....	....	11.69	60.40	....	....	....	....	....	As rolled	74400	122300	26.0	30.0	15.3	38.0	43.0	84270
52	Nichrome	0.81	1.50	0.58	....	....	12.8	66.0	....	....	....	....	....	As rolled	74400	122300	26.0	30.0	15.3	38.0	43.0	84270

H. R. Steel = Heat-Resisting Steel. O. H. = Oil Hardened. T. = Tempered. A. C. = Air Cooled. A. H. = Air Hardened. W. Q. = Water Quenched.

their own laboratory they have, however, compared a large number of steels and alloys of various compositions, at selected temperatures, and in Table XXXI the results of tensile tests at ordinary temperatures and at 1472 degrees Fahr. (800 degrees Cent.), together with the analyses and heat treatments, will be found.

The actual conditions of test were as follows:—The test pieces were 0.357 inch in diameter, with a parallel length of $1\frac{1}{4}$ inches. The specimen was heated in situ in an electric resistance furnace. The time taken to obtain the temperature was three-quarters of an hour to one hour, and then the selected temperature of 1472 degrees Fahr. (800 degrees Cent.) was maintained for half an hour before the test piece was pulled. The speed of pulling was in all cases at the rate of a quarter of an inch elongation per minute. It is well appreciated that the results derived from a tensile test at high temperatures should be interpreted in a different manner from those obtained from such tests at ordinary temperatures; but when allowance is made in accordance with existing knowledge, such values sufficiently afford a means of comparison. A careful scrutiny of the data given in this table shows the extent to which, by modifying the composition of steel, its strength at high temperatures may be very materially improved.

It will be seen that wrought iron at 1472 degrees Fahr. (800 degrees Cent.) gives a value so low as 4550 pounds per square inch (2.03 tons per square inch), and this is of interest as a basis of comparison for the other materials. Mild carbon steel gives a value of 8960 pounds per square inch (4 tons per square inch), while the highest value given for any of the ordinary nonheat resisting steels, can be taken to be under 17900 pounds per square inch (8 tons per square inch). It will be seen that chromium, even when added up to 14 or 18 per cent, when the carbon is very low and in the absence of other elements, does not increase the strength at high temperatures. It will be seen that nickel alone, even when added in considerable quantities, does not result in very high values at this particular temperature. It will also be seen that if tungsten is added along with the chromium, or if this element is added along with the nickel, no outstanding result is obtained. It will, however, be clear that if tungsten is added in the presence of both nickel and chromium, and providing that a fair percentage of carbon is present, then maximum stress values

are obtained of 44,800 to 56,000 pounds per square inch (20 to 25 tons per square inch) as compared with 4500 to 9000 pounds per square inch (2 to 4 tons per square inch) for ordinary iron and steels.

This data, therefore, experimentally establishes the position of that very interesting class of chromium-nickel-tungsten steels which are now being used in increasing quantities.

Turning now to the discussion of the general problem dealt with, the author would like to be able to give satisfactory explanations of—

- (1) Why the characteristics of steel are so modified with increasing temperature.
- (2) Why the added elements modify the properties of the steel at the high temperature in the manner disclosed.

The whole of the explanation turns upon an understanding of the nature of cohesion, and that again awaits the more complete elucidation of the nature of the atom and the electron. Whether such an understanding will help to produce materials of exceptional characteristics is problematical, since, even when our knowledge of the atom and its fields of force is complete, we shall still have to await the next phase, which obviously consists in learning how to make use of that knowledge. Progress will probably take the same line as in the past, i.e., by experimentally determining, in a more or less empirical manner, the various factors which affect the cohesive forces. It is, of course, extremely desirable to know many things. For instance, what determines the space lattice with which the various atoms crystallize; why such different space lattices behave differently, as clearly shown by the figures herein stated; the causes of different solubilities; whether compounds can exist as such in solid solution; a visualization of the mechanism of the effect of the speed of application of stress.

As regards slip, the author has always been led to the conclusion that the smaller the crystals, the higher the resistance, owing to the multiplication of diverse orientations, whereas evidence would show that those steels have greatest strength at high temperature, which consist of very considerably sized crystals, thus leaving the resistance to slip to be mainly due to interatomic forces in their effect in influencing the intrinsic resistance of individual crystals to slip and rupture.

With regard to (1), when a tensile test piece is stressed, motion of the atoms in relation to one another takes place, with the resulting elastic deformation. After passing a certain value of stress, plastic deformation occurs. This is associated with slip along certain planes, and the movement is constrained to the degree to which the progressive balancing of the effort applied in overcoming the interatomic forces, has taken place. If the stress applied is high enough, deformation proceeds until rupture occurs. At higher temperatures the effort required to overcome the interatomic forces is less, owing to the modification in these forces with temperature. Under static loads, below the continuous creep limit, the test piece will elongate elastically at first, and then plastically, until the opposition, due to resistance to slip, balances the applied load. With greater loads the balance cannot occur, and the piece elongates until fracture takes place. Increasing temperature will decrease the resistance to slip, and hence "continuous creep" stress is lowered. With rapid loading, as in the case of a normal short-time tensile test, time is not allowed for the test piece to develop the amount of deformation which for the temperature and stress would otherwise occur. In consequence, the load required to fracture is greater than in the case of continuous loading. The difference between the two, increases with rise of temperature and with increase in the rate of application of the load. The influence of the reduction of area of cross-section during the test, must be considered as regards its influence in increasing the effective stress upon the material.

With regard to (2), in our actual present ignorance of the nature of slip, it is difficult to discuss the influence of the various elements introduced into the material. The author presumes—and indeed there is ample evidence that such is the case—that if the stress required to break the material at 1470 degrees Fahr. (800 degrees Cent.) under the ordinary tensile test is higher, then the elastic range and also the "continuous creep" stress are raised. Discussing, then, these general phenomena, it seems fair to postulate that the kind of atoms most likely to prevent slip, which is clearly the means by which improvements in these steels are made, would be those which, on account of the nature and magnitude of their fields of force, would cause most disturbance of the lattice. This would provide an influence operating at all temperatures, but

modified by the mobility of the atoms coincident with the temperature. Unfortunately, the strength at high temperature bears little relation to the strength at low temperature. Nickel is an element with a similar atom to iron, and crystallizes in the same manner at high temperatures; it would, therefore, not be expected to increase the strength much at such temperatures, when added to iron. It is interesting to note, as is well known, that a critical percentage of nickel increases the strength of iron at ordinary temperatures five fold; at 1470 degrees Fahr. (800 degrees Cent.) the effect of hardening is small. Chromium is an atom approximately similar to iron in size, and which crystallizes with a body-centered configuration. Reference to the experiments (Table XXXI) will show that neither at ordinary temperatures, nor at 1470 degrees Fahr. (800 degrees Cent.), does this element when added alone, even when present in large proportion, materially harden the steels, and yet it would appear to be of material help in providing great strength at high temperature. It might be deduced from the experiments, that nickel had some little influence in hardening up the iron, but that chromium had less. The two elements together certainly resulted in making it necessary to apply a stress several times greater at 1470 degrees Fahr. (800 degrees Cent.), than in the case of iron. The addition of tungsten in relatively small quantities in the presence of the elements nickel and chromium, without carbon, has not been determined. If however, the same amount of tungsten is added to iron alone, the result is negligible, and, incidentally, if the tungsten is added with only chromium present, such is also the case; likewise, if only nickel is present. One has, therefore, to consider that the effect to be explained is that tungsten added to iron in the presence of a sufficient quantity of nickel, chromium and carbon, produces this effect, yet, clearly, there is also an optimum carbon content. Now all that can be said is that tungsten is a heavier and larger atom, and the implication is that it should increase the strength of the iron, but why should it need a critical accompaniment of carbon, chromium, and nickel for strength at high temperatures, and why should its influence not be more marked at ordinary temperatures? It would appear that its influence is most effective when added to alloys in which the iron throughout the whole range of temperature exists in the gamma condition, the most successful of the steels being in the austenitic condition.

Scale Resistance of Heat Resisting Steels

As regards the problem of throwing light upon the nature of the attack at high temperatures, it must at once be conceded that this is extremely difficult. It can be approached from the standpoint of corrosion at ordinary temperatures; and, indeed, in the literature of the subject, it is common to find the rustless and heat resisting steels dealt with together. The explanation of the phenomenon of resistance, or, to be more accurate, relative resistance at high temperatures, may be similar to that of the phenomenon of rust resistance, the resistance being determined by the formation, or otherwise, and the characteristics of, a protective film of a composition determined, in the first place, by the analysis of the steel, and in the second place, by the composition of the gaseous media. Experimentally, the subject is difficult, if only on one account: great care may be taken in purifying the gases used to produce the atmosphere required, but it should always be remembered that all the steels contain carbon, sulphur and hydrogen in varying, though in the latter cases, small, percentages, and at the high temperatures considered, these elements react with the gaseous medium. Thus small quantities of the products which such elements may form, will be present, and will require to be considered in any theoretical handling of the results. The importance of such percentages of substances, other than those directly under study, has been well emphasized in the investigations of corrosion at ordinary temperatures, of Friend, Evans, and others; it was established by Ariëns Kappers in 1872, that sodium and potassium did not oxidize in dried oxygen, by Cooper in 1882 that chlorine was without action on several metals in the absence of water; while Baker in 1883 established the astonishing fact that purified charcoal could be heated to redness in dried oxygen without burning.

As regards the actual experiments to which the author will now refer, he would say that, in all cases, unless otherwise stated, the samples were approximately 1.25 centimeters in diameter, and weighed about 30 grams (1 ounce); the index figure given is the increase in weight in milligrams per square centimeter of surface. A standard finish, viz., 00 emery, was given to all the cylinders. Thus the data obtained are all strictly comparable. The duration of the exposure was twenty-four hours,

Table XXXII

Influence of the Atmosphere, Pure and with Various Additions, on a Mild Carbon Steel (G)

Condition of Atmosphere	Weight of Samples, Grams	Increase of Weight, Grams	Index Figure
Pure air	21.7844	0.5800	55.238
Atmosphere	21.0978	0.6117	57.166
Pure air + 2% SO ₂	20.8553	0.6843	65.173
Atmosphere + 2% SO ₂	19.7816	0.6905	65.762
Atmosphere + 5% SO ₂ + 5% H ₂ O	20.4646	1.5242	152.420
Atmosphere + 5% CO ₂ + 5% H ₂ O	22.4074	1.1048	100.436
Pure air + 5% CO ₂	22.1328	0.9303	76.884
Pure air + 5% H ₂ O	20.3436	0.8089	74.211

With a view to determining the effect of the influence of sulphur dioxide, carbon dioxide and H₂O in facilitating scaling, the author exposed a series of mild steel test pieces and chromium-nickel rustless steel test pieces at 1650 degrees Fahr. (900 degrees Cent.), with the results shown in Tables XXXII and XXXIII. These data do indicate the acceleration of attack brought about by the presence of these influences. It was realized that it was desirable

Table XXXIII

Influence of the Atmosphere, Pure and with Various Additions, on a Chromium-nickel Rustless Steel (N)

Condition of Atmosphere	Weight of Sample, Grams	Increase of Weight, Grams	Index Figure
Pure air	34.7058	0.0062	0.403
Atmosphere	34.5083	0.0071	0.461
Pure air + 2% SO ₂	25.5649	0.0107	0.859
Atmosphere + 2% SO ₂	23.4008	0.0136	1.126
Atmosphere + 5% SO ₂ + 5% H ₂ O	23.7758	0.0439	3.678
Atmosphere + 5% CO ₂ + 5% H ₂ O	31.5332	0.0678	4.582
Pure air + 5% CO ₂	31.3954	0.0176	1.175
Pure air + 5% H ₂ O	31.1554	0.0516	3.240

to endeavor to couple up the response at ordinary temperatures with that at 1650 degrees Fahr. (900 degrees Cent.); but to do this satisfactorily with the whole of the gaseous media was a very big task, and it was therefore decided simply to experiment, at this stage, with the ordinary atmosphere, but using three steels, i.e., a mild carbon steel, a 14 per cent chromium steel, and the one used in the previous experiment, containing 18 per cent chromium and 8 per cent nickel. The results will be found in Table XXXIV. It is clear from these figures, that the chromium steel (K) is mark-

Table XXXIV
Atmospheric Tests on Three Steels

Testing Temperature		Mild Steel	Chromium Steel	Nickel-Chromium
Degrees Fahr.	Degrees Cent.	(G) Index Figure	(K) Index Figure	Steel (N) Index Figure
212	100	nil	nil	nil
392	200	0.033	0.013	nil
572	300	0.127	0.040	0.020
752	400	0.454	0.081	0.040
932	500	0.622	0.093	0.040
1112	600	4.636	0.200	0.133
1292	700	11.917	0.399	0.223
1472	800	44.914	0.767	0.395
1652	900	57.166	1.073	0.461
1832	1000	135.777	66.671	21.820
2012	1100	208.000	165.270	72.301
2192	1200	399.877	261.000	177.660

edly superior to the mild steel (G), but that whilst both steels are unaffected at 212 degrees Fahr. (100 degrees Cent.), they are both attacked at 392 degrees Fahr. (200 degrees Cent.), though in different degrees. There is a great acceleration in the attack on mild steel on approaching 1110 degrees Fahr. (600 degrees Cent.), but the similar acceleration in the case of the chromium steel is postponed until 1658 degrees Fahr. (900 degrees Cent.). A comparison of the results obtained with the nickel-chromium steel (N), indicates clearly the increased resistance obtained by the further modification in composition. The outstanding feature of these experiments, to the author's mind, is the definite attack obtained at such low temperatures in the case of all three steels. According to common conceptions, the zone of temperature from 400 to 930 degrees Fahr. (200 to 500 degrees Cent.) would hardly be associated with the heat resisting problem under consideration, yet clearly the attack appears to be of the same nature as that which takes place at the higher temperatures, but simply of a different order.

As regards the resistance of materials to industrial gases, continuous investigations are in hand in their laboratories, and probably it will be useful to present some of the data. One of the conditions of test is the atmosphere of an unenclosed gas muffle, and the composition which may be taken as representative of the atmosphere, is as follows.

	Per Cent
Nitrogen	67.70
Oxygen	1.34
Carbon dioxide	4.75
Steam	21.10
Sulphur dioxide	0.003
Carbon monoxide	5.10

Table XXXV
Analyses of Materials

Sym- bol	Material	Condition	C	Mn	Si	S	P	Per Cent Cr	Ni	W	Cu	Fe
A	Pure iron	Normalized 1742 degrees Fahr.	0.04	0.01	0.01	nil	nil	.....	0.02	.....	.....	99.92
B	Chromium	As cast	0.16	0.02	0.40	.....	.....	98.10	.....	.....	.....	1.80
C	Nickel	As cast	0.04	.....	.....	.....	.....	.....	99.58	.....	.....	0.38
F	Tungsten	Hard drawn	.....	nil	.....	.....	.....	.....	.....	99.99	.....	.....
Q	Mild carbon steel	Normalized 1652 degrees Fahr.	0.17	0.67	0.18	0.012	0.018	.....	0.25	.....	.....	98.70
H	3% nickel steel	Oil hardened 1562 degrees Fahr. tempered 1166 degrees Fahr.	0.34	0.60	0.29	0.021	0.012	.....	3.25	.....	.....	95.49
I	36% nickel steel	Air cooled 1742 degrees Fahr.	0.24	0.40	0.16	0.020	0.015	0.09	36.90	.....	.....	62.17
J	Silicon-chromium steel	Air cooled 1922 degrees Fahr. tempered 1562 degrees Fahr.	0.50	0.37	3.04	0.01	0.01	8.28	0.16	.....	.....	87.63
K	Chromium steel	Oil hardened 1832 degrees Fahr. tempered 1472 degrees Fahr.	0.32	0.25	1.32	0.009	0.016	13.12	0.29	.....	.....	85.67
L	Chromium steel	Air cooled 1652 degrees Fahr.	0.09	0.39	0.37	0.011	0.015	18.53	0.26	.....	.....	80.334
M	Chromium-nickel steel	Air cooled 2102 degrees Fahr.	0.11	0.34	0.21	0.011	0.013	14.84	10.16	.....	.....	74.816
N	Chromium-nickel steel	Air cooled 2102 degrees Fahr.	0.12	0.28	0.31	0.008	0.014	17.74	8.06	.....	.....	73.47
O	Nickel-chromium steel	As rolled	0.35	1.36	0.21	0.021	0.013	10.90	35.15	.....	.....	52.00
P	Chromium-nickel-silicon steel	Water quenched 1832 degrees Fahr.	0.58	0.36	4.00	0.020	0.017	15.54	8.14	.....	.....	71.43
Q	Chromium-nickel-tungsten steel	As rolled	0.30	0.52	1.46	0.02	0.017	17.74	7.0	4.23	.....	68.713
R	Nichrome	Air cooled 1742 degrees Fahr.	0.06	0.89	0.71	.....	.....	11.69	60.40	.....	.....	26.24
S	Cast iron	As cast	.....	.....	1.13	0.125	0.58	.....	.....	.....	.....	94.24
T	15% silicon iron	{ Gr. C. O. C. Gr. C. C. C.	0.68	0.76	14.30	0.045	0.731	.....	.....	.....	.....	83.92
U	Monel metal		0.03	0.21	.....	.....	.....	.....	.....	.....	.....	.....
	Hot rolled		0.14	1.00	0.63	.....	.....	.....	69.98	.....	27.17	1.67

Table XXXVI
The Influence of Industrial Gases

Symbol	Material	Complex gas at 1652° F. Index figure	Muffle at 1652° F. Index figure
A	Pure iron	114.012	95.34
B	Chromium	2.051	1.00
C	Nickel	5.222	16.83
G	Mild carbon steel	80.225	73.104
H	3% Nickel steel	72.893	45.30
I	36% Nickel steel	30.058	27.70
J	Silicon-chromium steel	0.84	0.506
K	Chromium steel	18.319	20.50
L	Chromium steel	1.252	1.38
M	Chromium-nickel steel	6.000	3.84
N	Chromium-nickel steel	2.699	0.326
O	Nickel-chromium steel	2.534	1.01
P	Chromium-nickel-silicon steel	0.689	0.061
Q	Chromium-nickel-tungsten steel	0.43	0.175
R	Nichrome	1.397	0.765
S	Cast iron	86.000	33.80
T	15% Silicon iron	78.434	13.734
U	Monel metal	68.676	1.55

The other atmosphere is that produced by a complex gas, synthetically produced as representing the products of combustion, of the following composition:—

	Per Cent
Nitrogen	72.95
Oxygen	5.00
Carbon dioxide	12.00
Steam	10.00
Sulphur dioxide	0.05

In Table XXXV will be found a statement concerning the analyses and conditions of the materials tested, and it will be seen that the list has been so put together as to make easy reference possible with regard to the resistance to scaling of the materials generally available.

In Table XXXVI will be found a statement of the actual index figures obtained from this series of results in the two atmospheres, at 1652 degrees Fahr. (900 degrees Cent.). On considering the influence of these industrial gases on the various samples, it will be seen that, although only one temperature, 900 degrees Cent., is being considered, there are interesting facts to be discerned. Pure iron (A), as would be expected, is very badly attacked, chromium (B) is very resistant, while compared with

iron, nickel (C) gives a good account of itself. Mild carbon steel (G) is more resistant than the pure iron (A), possibly on account of the protection afforded by its carbon content. The influence of nickel is well illustrated by the steels containing 3.0 and 36 per cent respectively (H and I), and it will be seen that the effect is undoubtedly to produce increased resistance. The silicon-chromium steel (J) is, curiously, much more resistant even than chromium. In the two chromium steels (K and L), 13 per cent chromium undoubtedly had a profound influence upon the behavior of the alloy, but by increasing the percentage to 18.0, a resistance of the same order as that of chromium (B) is obtained. On studying the steels (M), (N) and (O), containing both nickel and chromium, a high but variable resistance due to the variable proportions of the elements is found; (N) gives the most satisfactory results, but it is interesting to compare (M) and (K), in which the chromium is roughly comparable, but in which there is the outstanding variable of 10 per cent nickel in (M), and a greatly improved resistance. The optimum results obtained from (N) are seen to be still further improved in the cases of either (P) or (Q) by the addition of silicon and tungsten respectively. Nichrome, as would be expected, gives very good results, but it is not equal to either (J), (P) or (Q), which are charged with a far smaller amount of the added metals. The cast iron (S), the 15 per cent silicon iron (T), and the Monel metal results are of interest by way of comparison with the general series.

It is to be deduced from these figures that the resistance of iron is greatly increased by the addition of either chromium or nickel, or both; the addition of silicon or tungsten still further increases the resistance of such alloys.

A comparison of these results would indicate quite clearly that the "complex" gas, as a general representative of products of combustion, is much more active in attacking the samples than the muffle atmosphere: the latter series of tests was introduced to enable a comparison with the other more "experimental" tests to be made in an empirical practical manner. Broadly speaking, the greater activity of the "complex" gas must be accepted, and it is, therefore, of interest to compare the two gaseous atmospheres. The "complex" gas contains more carbon dioxide, oxygen, and sulphur dioxide, and very much less steam. The author is of the

opinion that the increased attack is due to the increased percentages of CO_2 and SO_2 , particularly of the latter.

In one of the author's papers to which he has just referred,¹⁶¹ an account is given of fundamental experiments with a view to deducing the effect of the various elements. The alloying of chromium with iron in the production of rustless and heat resisting steels, has been previously well dealt with in technical literature. The patent history of this and other countries also yields much information. The work of Brearley, Haynes, Pasel, Becket, the author, and others, laid a sound foundation to the knowledge of that particular field. An interesting paper by McQuigg¹⁶² discusses the influence of chromium in increasing the heat-resistance of steels, while the American Society for Testing Materials Symposium of 1924 did much to focus attention on the subject, notable papers being given by Johnson and Christiansen, Hunter and Jones, and Fahrenwald. The American Symposium, to which reference has just been made, has also done much to extend the use of alloys containing nickel in addition to chromium, thus encouraging the utilization of the additive advantage of that element. The apparently anomalous effect of nickel in assisting in the protection of the steel of which it is a constituent, may probably be explained by the influence of that element in causing the formation of a particular kind of protective layer. That nickel is a valuable element in these heat resisting steels has also been established by other investigators. Sir Robert Hadfield,¹⁶³ went so far as to suggest that the inclusion of nickel was responsible for a great step forward. Monypenny¹⁶⁴ described the increased resistance due to the addition of this element; and the same deduction is also to be made from the paper by Elliott and Willey.¹⁶⁵

The influence of silicon and tungsten in further increasing the resistance, would appear to be fully established. In the case of tungsten, this effect is certainly anomalous, since, in the author's fundamental experiments, an abnormal attack in oxygen was dis-

¹⁶¹W. H. Hatfield, *Journal*, Iron and Steel Institute, Vol. CXV, 1927.

¹⁶²McQuigg, *Proceedings*, American Institute of Mining and Metallurgical Engineers, Vol. LXIX, 1923, p. 831.

¹⁶³Robert Hadfield, Paper read before the Institute of Marine Engineers, January 11, 1927.

¹⁶⁴Monypenny, "Stainless Iron and Steel," London, 1926, Chapman and Hall, Ltd.

¹⁶⁵Elliott and Willey, Paper read before the Congress of Chemists, July 20, 1926: *Chemistry and Industry*, July 30, 1926, p. 526.

closed, a heavy attack in steam, but a materially diminished attack in CO_2 and SO_2 . It might, of course, be deduced that the additive protection accorded by the metal is in line with its behavior toward the anhydrous acids CO_2 and SO_2 , particularly the latter.

The main feature of these notes is the attempt to establish quantitatively the fact that these added elements do indeed produce steels which satisfactorily resist attack at high temperatures, and among such can safely be cited certain compositions in the chromium, the silicon-chromium, chromium-nickel, chromium-nickel-silicon and chromium-nickel-tungsten series. Some of these steels have extremely satisfactory characteristics as regards resistance to corroding influences under the conditions studied, and are fitted for much wider service than that in which they are at present employed.

In a consideration of this work, it should be borne in mind that, apart from the simple metals, the materials selected for the research largely represent actual steels which have seen service conditions. It will be realized that with so many elements to work upon, the combinations are almost without limit. It is the author's opinion that a proper appreciation of the possibilities of this field will enable the engineering world to develop successfully the various projects so dependent upon the satisfactory resistance of steel at high temperatures. Some of the steels dealt with in the paper are already complex in composition and constitution, but experiment may finally establish that the addition of cobalt, molybdenum, aluminum, and other elements may result in further advantages as regards the desirable characteristics. Suffice it to have shown that the last few years have produced some special steels largely fulfilling the requirements of high strength at high temperatures, coupled with an excellent degree of resistance to scaling under such conditions.

SECTION VII

TOOL STEELS AND CUTLERY

In this section the author proposes to discuss a few questions arising in regard to the special class of steels coming under the above general heading.

Carbon Tool Steels

The carbon tool steels are an extremely interesting class, and for many purposes will repay careful study and knowledgeable treatment. In England, the higher grades of these steels are still manufactured by the crucible process and, as mentioned previously, this process lends itself admirably to producing homogeneous clean steel. Swedish iron is usually the base material, and undoubtedly crucible steel made from Swedish material has deservedly earned a very high reputation. Among those engaged in the manufacture and distribution of these steels, it is not unusual to hear them talk of that mysterious quality "body." When the Iron and Steel Institute visited Stockholm some eighteen months ago, a number of us had the pleasure of looking over the magnificent research laboratories of the Metallographic Institute, and during the visit, the author found an opportune moment to have the question put—"Will Professor Benedicks kindly define and explain to us the nature of 'body' in Swedish iron and steel?" The distinguished Professor, without any hesitation at all, answered in his most charming manner, "My mother, she told me not to tell such things."

Now as to whether and to what extent the best crucible steels of this class possess this mysterious characteristic, the author is unable to be dogmatic, but of this he is perfectly sure, that such steels, made from the purest materials under the best conditions, can be considered to possess the combination of qualities to which it is not surprising that time has given the mysterious appellation of "body." The behavior of a cutting tool, under service conditions, is determined by so many factors, many of which are only empirically controlled under what is termed "good practice", that it is difficult to determine, without an actual cutting test, what the exact merits of a particular steel are. Were the author asked to define the word "body", he would be a little more explicit perhaps than Professor Benedicks was on the memorable occasion previously referred to, and he would define the characteristics as "that outstanding reliability under strenuous conditions, which cannot be determined by simple direct tests, but can only be experienced under actual practical service conditions." It is naturally a foregone conclusion that an all-round high standard of

technique as regards material, method of production and final heat treatment, must be reflected in the service obtained.

A careful consideration of the various details which must be controlled to obtain the maximum reliability and efficiency, entitle a really good tool steel to be looked upon as an undoubtedly super-fine product. The materials must be carefully selected, the composition must be very well controlled, and the method of melting must include adequate "killing." The mold must be of proper design and the teeming done at the correct temperature and speed, with the care necessary to ensure that the feeder head is effective, and that the frozen ingot is free from pipe and gas holes, entrapped dirt or laps. The heating for forging should be done intelligently, since too rapid heating may cause clinks, exceeding a certain temperature may introduce the overheated condition, whilst insufficient heating or continuation of the hammering too long or too heavily, may, during the working down stage, result in internal rupture of the material. A proper amount of work upon the material is also desirable. Add to this that the condition prior to the final hardening must be such that the final condition, as will be shown later, does not reflect after hardening an unsatisfactory condition of the material, and it will be agreed that when all this is achieved, the technician may be excused if he claims some mysterious merit of the material.

Generally speaking, these carbon tool steels range from 1.5 down to about 0.7 per cent carbon, and generally have a low manganese content. It is very desirable that, in heating for the forging operation, such material as just mentioned shall not be overheated, and the author considers that an initial temperature of 1920 to 2010 degrees Fahr. (1050 to 1100 degrees Cent.), according to carbon content, should not be exceeded, and that work should not be put upon the steel after the temperature has fallen to the neighborhood of 1292 degrees Fahr. (700 degrees Cent.).

Assuming that such steel has been carefully cast into small ingots of suitable shape with adequate feeder heads, and has been forged under proper conditions and given good technique in the final hardening and tempering operations, the most delicate and intricate tools of the highest characteristics and reliability can be produced. Particularly as regards the higher carbon steels, it is always well to anneal subsequent to the forging operation.

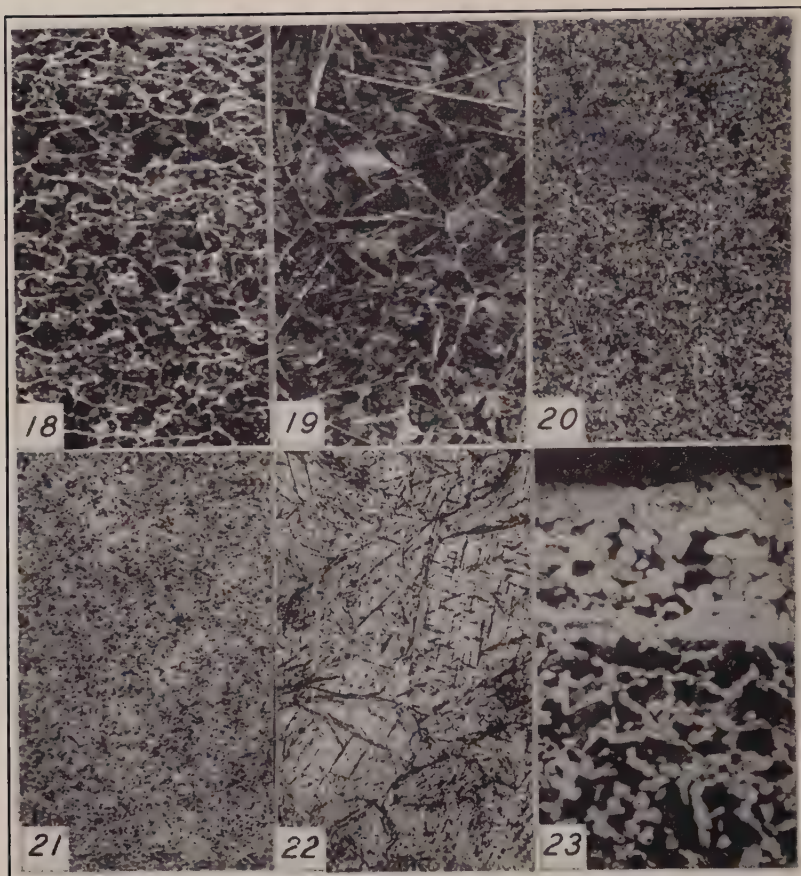


Fig. 18—Photomicrograph Typical of File Steel in the Rolled Condition. Fig. 19—Same Steel as Fig. 18 Heated to 1742 Degrees Fahr. (950 Degrees Cent.) and Air Cooled. Fig. 20—Photomicrograph of File Steel Annealed at 1364 Degrees Fahr. (740 Degrees Cent.) for 4 Hours After Forging. Fig. 21—File Steel Well Annealed and Hardened. Samples in Figs. 18, 19, 20 and 21 Etched in Picric Acid. $\times 200$. Fig. 22—Photomicrograph of Carbon Steel Rock Drill Hardened from Too High a Temperature. Etched in Picric Acid. $\times 100$. Fig. 23—Photomicrograph of the Bore of Hollow Carbon Steel Drill Showing Decarburization. Etched in Picric Acid. $\times 200$.

The microscope is invaluable in the study of such tool steels. While the understanding of the microstructure of purely iron-carbon steels is well understood, it cannot be said, that the same remark applies to complex alloys steels, but, nevertheless, the structures are always traceable to composition and past history, and give valuable information.

In no instance is this better illustrated than in the case of

file steel. Fig. 18 is typical of the rolled condition in which the carbon in excess of the eutectoid composition is present in the form of membranes of carbide of iron, with the general structure elongated in the direction of rolling. Fig. 19 illustrates the same steel after air cooling from 1742 degrees Fahr. (950 degrees Cent.), and the appearance of the needles of carbide is distinctive. Hardened from this condition, the martensitic matrix would be rendered brittle by the dispersion through it of this form of the carbide. By a suitable low temperature annealing the structure shown in Fig. 20 is obtained, and hardening from this condition gives the correct structure for hardened file steel as shown in Fig. 21.

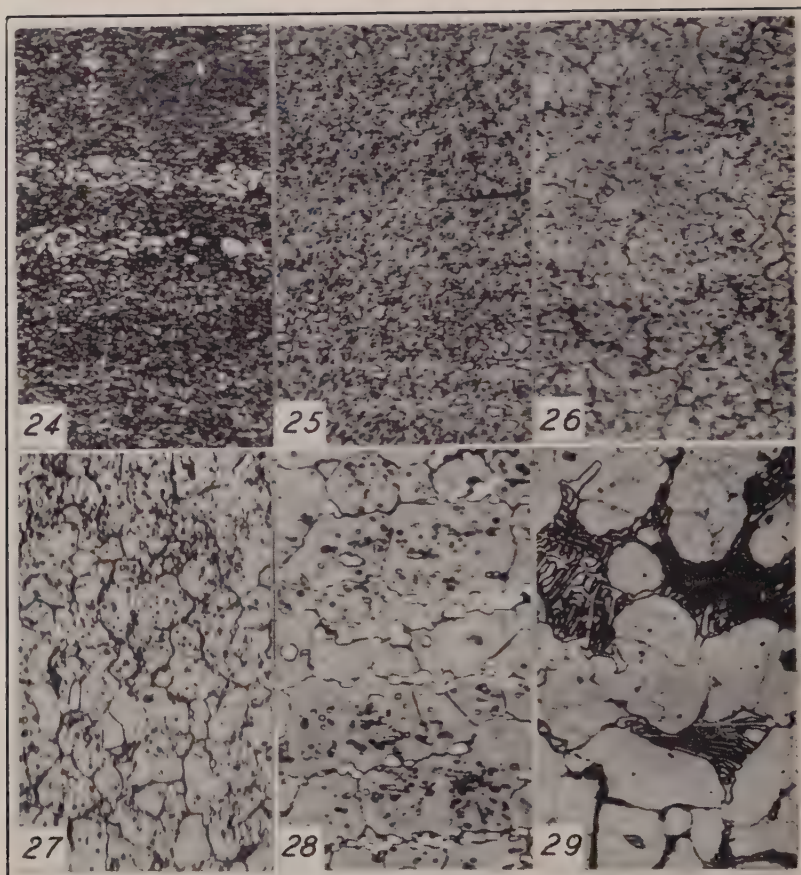
The same effect is common to other such high carbon steels, and Fig. 30 indicates the structure of a good safety razor blade, which obviously must have received the correct annealing treatment prior to being hardened.

Should carbon tool steel be hardened from excessively high temperatures, brittleness ensues and this effect may generally be detected as it is reflected in the microstructure, as shown in Fig. 22 which is taken from an example of carbon rockdrill steel. Again excessive time-temperature decarburizing effects are readily recognized as shown in Fig. 23 which illustrates a section through the bore of a hollow carbon steel drill.

High Speed Steels

These steels are made over a wide range of composition and it may be of interest to you to have a few comments upon the subject. The metallography is complex and though many years have elapsed since the notable advances of Mushet and of Taylor and White, the subject is obviously still treated in an empirical fashion. The results of numerous valuable researches have been published over recent years, but we have still much to learn. All the care necessary in the production of carbon tool steel is required with additional steps to ensure homogeneity in composition, particularly in the steels richest in special elements.

The author has frequently been amused by the rival claims of different makers of such steels, claims out of all accord with actual facts. The steels vary in merit according to analysis, but each varies so much according to the treatment given, and the actual conditions under which comparative tests can be made are so com-



Photomicrographs of High Speed Steel. Fig. 24—Annealed. Fig. 25—Oil Quenched at 2102 Degrees Fahr. (1150 Degrees Cent.). Fig. 26—Oil Quenched from 2282 Degrees Fahr. (1250 Degrees Cent.). Fig. 27—Oil Quenched from 2372 Degrees Fahr. (1300 Degrees Cent.). Fig. 28—Quenched from 2507 Degrees Fahr. (1375 Degrees Cent.). Fig. 29—Air Cooled from 2552-2642 Degrees Fahr. (1400-1450 Degrees Cent.). All Specimens Etched with 2 Per Cent Nitric Acid in Alcohol. All Magnifications $\times 500$.

plex, that such tests are only fair when all variables are eliminated. The optimum heat treatment for one steel is not necessarily the best for another.

The material which is being cut should be uniform as regards composition, condition and hardness. This is difficult to achieve in a bar of large diameter. The geometry of the tool should be carefully standardized; the speed, cut and feed be unified and under adequate control; while obviously each high speed steel

should be given its optimum hardening and tempering treatment. Under such conditions accurate comparisons of merit can be made.

A few of the conclusions arrived at as a result of researches in the Brown-Firth research laboratories may be stated. The optimum carbon content lies between 0.55 per cent and 0.80 per cent. Below 0.55 per cent, there is difficulty in obtaining full cutting hardness. If above 0.80 per cent, the tools are not as resistant to shock, and furthermore, excessive wastage in manufacture occurs. Manganese, when added to excess, is a disability. Silicon may vary within normal limits without affecting the efficiency. The chromium generally should be within the limits 3.5 to 4.5 per cent. The tungsten may advantageously be replaced by molybdenum and cobalt. Long experience shows the advantage of 1.0 to 1.5 per cent of vanadium. If in the final stages of heating up, the heating is done slowly, the effect is detrimental from two causes; decarburization and coarsening of grain. The optimum range of temperature for hardening is 2370 to 2450 degrees Fahr. (1300 to 1340 degrees Cent.), and the more rapid the cooling from the hardening temperature, the better will be the results with, of course, the exception that, under certain conditions, particularly of design, water quenching may produce cracking. Tempering to 1020 or 1110 degrees Fahr. (550 or 600 degrees Cent.), after hardening has definitely a beneficial effect upon the average life of the tool.

Hardness tests at normal temperatures give no indication of the possibilities of a cutting tool, and even if such quantitative tests are done at the higher temperatures, the figures are sometimes misleading. Properly controlled cutting tests as before described are the only reliable means of comparison. High speed steels have long been studied under the microscope, and in post mortems the microscope is invaluable. This is not because we completely understand the compositions of the constituents, but we are able to recognize their form, size and distribution and thereby gain much knowledge of the thermal history of the steel. This is well illustrated by photomicrographs taken from a steel containing 18 per cent tungsten, 3.5 per cent chromium and 1.5 per cent vanadium. Fig. 24 represents the structure of the steel in the annealed condition previous to the subsequent treatments. This particular photomicrograph is selected as containing the white constituent in a

somewhat emphasized form. This constituent has been claimed to be carbide by some, tungstide by others; it most probably in this steel is a complex carbide of tungsten, iron and chromium. However, a knowledge of its constitution has not prevented the utility of the general structures obtained as evidenced by those depicted in Figs. 25, 26 and 27 which show the effect of gradually increasing the hardening temperature from 2100 to 2370 degrees Fahr. (1150 to 1300 degrees Cent.). The general effect appears to be the tending toward completion of the solid solution. Much higher temperatures as shown in Fig. 28 result in a considerable growth in grain size; 2370 to 2450 degrees Fahr. (1300 to 1340 degrees Cent.) has been established as the best hardening temperature. Fig. 29 is of interest as definitely indicating that at temperatures in the neighborhood of 2550 degrees Fahr. (1400 degrees Cent.) the solidus has been passed during heating and that partial liquefaction had taken place.

Cutlery

One of the most interesting practical investigations for which our research laboratories have been responsible, arose through the suggestion, years ago, that knives made of stainless steel did not retain properly their cutting edge. So persistent was the suggestion that it was considered desirable to investigate the matter thoroughly once and for all. The ordinary steel blade, cleaned, as it is, either on a knife board or in a machine, has the surface abraded every time it is cleaned, and obviously this very action tends to keep the cutting edge sharp: whereas, knives made of

Table XXXVII

	Brinell Hardness Numbers
Good shear steel carving knives	504, 510, 525, 508
Good shear steel table blades	510, 525, 525, 530
Good ordinary steel carving knives	525, 520, 508
Good ordinary steel table knives	525, 508, 510, 512
Good cast steel pocket knives	560, 575, 560 580
Good cast steel razor	625, 625, 640
Good stainless carving knives	500/520
Good stainless table blades	500/550
Good stainless pocket knives	550/600
Good stainless razor	625
Bad-cutting stainless knives	380, 360, 400
Bad-cutting ordinary knives	400, 390, 385

Size of Brinell ball employed = 3/32-inch diameter.

stainless steel are simply washed, wiped and put away. It is, of course, quite clear that all cutting tools, including knives, must be sharpened from time to time.

However, since the investigation had to be made, it was thought that the best policy to pursue was to secure many examples of thoroughly "good cutting" carving knives, table knives, pocket knives, razors, etc., possessed by our several friends and acquaintances. Having, therefore, secured an excellent array of such examples, we proceeded to determine in a very accurate man-



Fig. 30—Photomicrograph of an Excellent Razor Blade. Carbon 1.45 Per Cent, Manganese 0.13 Per Cent. Brinell Hardness 650. Specimen Etched with Picric Acid. $\times 200$.

ner, the composition, hardness, and any other characteristics that might have a bearing upon the subject, including the geometry of the cutting edges.

The hardness is clearly a predominating factor in determining the life of the cutting edge and it was instructive to find that each type of knife had a characteristic range of hardness as shown in Table XXXVII.

It will be seen that good carving knives and table knives had a range of hardness which can be taken as 500 to 530 Brinell; pocket knives were definitely harder, having a Brinell hardness number of between 550 and 600, while razors clearly had a much greater hardness, the values ranging from 600 to 650. The consistency of these results is extremely interesting, having in mind that many of these knives had been manufactured as long as 40 to 50 years ago, and most probably it was the exception if any modern technical knowledge as regards temperatures had been applied.

Reference to the table will show that in the case of indifferently cutting knives, whether they were of stainless or of ordinary steel, the hardness was very much down. In commenting upon the hardness of the blade, one might observe that if a knife is too hard it obviously has not been sufficiently tempered; if it is too soft it is because, either (1) it has not been properly hardened, or (2) it has been over-tempered, always providing that the steel was of the correct composition. During the course of our studies the nature of the actual cutting edge was studied, and, generally speaking, it can be considered that this factor cancels out, since the characteristics were common to the blades made from both the ordinary and the stainless steels; this is illustrated in Fig. 32 and 33. While

Table XXXVIII

	Carbon	Manganese	Per Cent			Chromium
			Silicon	Sulphur	Phosphorus	
Shear steel table blades	0.80/0.95	0.05	0.07	0.01	0.01	....
Shear steel carvers	0.80/0.95	0.05	0.07	0.01	0.01	....
Cast steel table blades	0.80/0.95	0.22	0.12	0.03	0.01	....
Cast steel carvers	0.80/0.95	0.22	0.12	0.03	0.01	....
Ordinary steel table blades	0.45/0.50	0.50/0.80	0.12	0.05	0.05	....
Ordinary steel carvers	0.45/0.50	0.50/0.80	0.12	0.05	0.05	....
Cast steel pocket knives	0.80/1.0	0.22	0.12	0.03	0.01	....
Cast steel razors	1.4 /1.5	0.22	0.12	0.03	0.01	....
Stainless cutlery	0.30 (about)	0.30	0.12	0.02	0.02	13.0 (about)

speaking of the quality of cutting edges, it is interesting to draw attention to the characteristics in this respect, of two carbon steel safety razor blades, see Figs. 34 and 35, one of which gave excellent results and the other very poor results. As regards the geometry, i.e., the angles formed by the cutting edges, these also cancel out, since the variations are common to the same type of blade irrespective of the type of steel employed.

In the old days, and even now to some extent, the cutlery trade has been content to buy steels of certain tempers. This is largely due to the fact that the high-class Sheffield cutlery upon which Sheffield's reputation has been built, was manufactured from steel produced by the cementation or carburization of Swedish wrought iron. The blister bars produced in this way were then either piled into faggots and hammered into bars to produce shear

steel, or they were broken up and melted in the crucible to produce crucible cast steel. It was left to the skill of the men who examined the broken blister bars to determine to which temper a particular bar belonged. In dealing with this matter I would not make a single criticism. The men who were responsible for the classification of the bars into the different tempers did their work extremely well. When, however, we come to a scientific consideration of cutlery, it is not enough to know the temper. We must know exactly how much carbon, manganese, silicon, sulphur, phosphorus or other element is present in the steel. We therefore, for instance, in our investigation dissolved up these excellent specimens of knives after performing our other tests upon them, and were thus enabled, by chemical analysis, to see exactly what their composition had been. The results of our investigations will be found in Table XXXVIII.

It will be seen that good shear steel cutlery has an extremely low sulphur and phosphorus, a low manganese content, and, what is most important, a carbon content ranging from 0.80 to 0.95 per cent. With regard to cutlery made from crucible steel produced by the melting of the blister bar, I would observe that analysis alone reveals little difference except a slight increase in the manganese and sulphur content. It can, however, readily be determined whether a knife is made from shear or cast steel, as will be shown later.

It will be seen that the pocket knives made from cast steel are a little higher in carbon than the table cutlery. When we come to the razor we find that the carbon has been increased up to and above 1.40 per cent.

It will be noticed in the table that we have included the analyses of knives made from ordinary steel. This ordinary steel is manufactured by either the Siemens or the Bessemer process, and attention might be drawn to the fact that the carbon is very much lower and the manganese very much higher.

If the analysis of stainless steel is examined in the table it will be seen that, curiously, the carbon is as low as 0.30 per cent while we have present 13 per cent of chromium. It is the presence of this chromium which renders possible the production of the stainless knife. The application of a high chromium steel for this purpose is to be credited to our research laboratories during the period

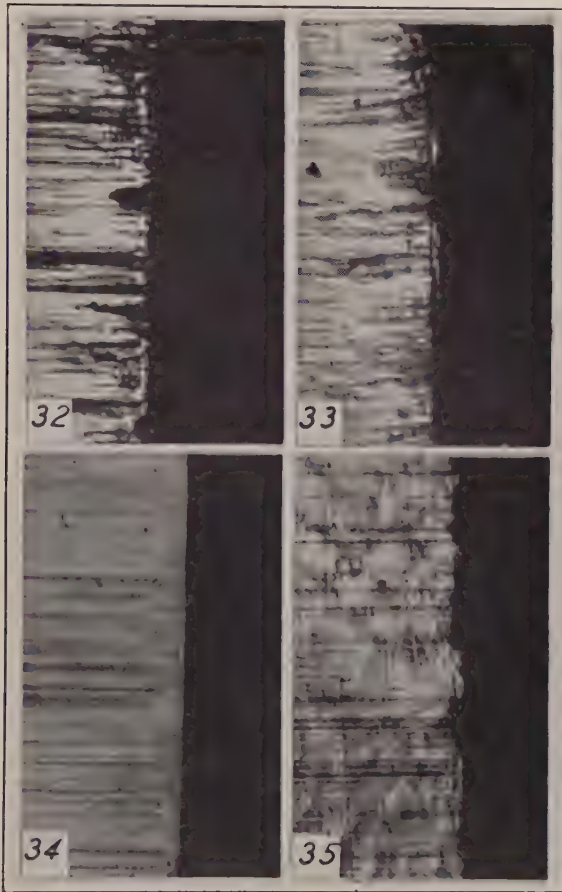


Fig. 31—Photograph Showing the Macrostructure of Table Knives.

when its work was supervised by my friend Mr. Brearley, and the development of stainless steel knives will undoubtedly rank as one of the most important metallurgical advances of recent years.

One very interesting, though perhaps not as useful, side of our investigations consisted of polishing the various blades and then etching them with an 8 per cent solution of copper ammonium

chloride. This reagent will be found to deposit copper on the blade, but this deposit should be removed while wet, and the knife rubbed with cotton wool and washed in a stream of water. The result is that in shear steel rather curious and pretty patterns are obtained, as shown in Fig. 31.



Photomicrographs Showing Fig. 32—Cutting Edge of Carbon Steel Knife. Fig. 33—Cutting Edge of Stainless Knife. Fig. 34—Cutting Edge of Good Safety Razor Blade. Fig. 35—Cutting Edge of Poor Safety Razor Blade. All Magnifications $\times 100$.

If these figures are studied it will be seen that by this means we get a concrete and definite knowledge of the manner of manufacture of the steel from which the blade was made. These lines

clearly indicate that the material is shear steel, and a careful consideration of them will even give one such precise information that one can determine whether the material employed was single shear or double shear, and, incidentally, how many bars were heated in each faggot. However, it is not proposed to say much on this subject except to point out that there is a ready method by which a shear steel blade can be distinguished from an ordinary cast steel blade, since the cast steel blade, under this treatment, does not give such a pattern if made from sound steel.

One might here, perhaps, make a few observations on what we consider to be matters where trouble is largely experienced in the manufacture of stainless knives. I have already pointed out that stainless steel hardens when cooled in the air from a high temperature, and it is therefore clear that before "flying out" cold, the rough blades should be suitably annealed at 1380 to 1400 degrees Fahr. (750 to 760 degrees Cent.). If the blades are suitably softened, as they may readily be, it is best to fly them out cold. If the blades are not annealed, then they must be flyed out at a dull red, heating to which temperature will do much to soften the blades. It is unnecessary to mention the importance, in the first place, of not getting the steel too hot during the forging operation, and, in the second place, not putting work on it after it has become too cold. With regard to the smithing operation, i.e., straightening before hardening, it will be clear that if the blades have not been annealed but are smithed after cooling from a high temperature, some of them will probably be cracked in this process. Perhaps one of the most important points to watch is that excessive scaling is not permitted when the steel is exposed to high temperatures. If the scaling is excessive, difficulty is encountered in producing a perfect surface by grinding. If any of this scale, or oxide of iron, is left in the final blade, it forms a seat of corrosion and becomes a very pronounced defect in the course of time.

As regards the method of putting on the name and identification marks, the only process to employ is that of etching. Etching can be done with ease and gives a very good result, while stamping in the name, results in scale being pushed into the letters in such a way it cannot be removed, and instances have been known where the scale so introduced into the blade has formed the seat of corrosion.

In conclusion, it might be pointed out that blades should not be ground in such a way that they become heated. If they do, discoloration is the result, and this discoloration is indicative of a condition of the blade in which it does not perfectly resist staining influences. After this discoloration has been produced it may be removed by further polishing, but even so, the blade is not as perfectly stain resisting as if it had been ground with care and had not been allowed to become unduly heated in that operation.

For a stainless blade to be perfectly satisfactory the steel must be of the correct composition. The next point is that it must have been satisfactorily hardened from a temperature of 1740 to 1830 degrees Fahr. (950 to 1000 degrees Cent.) and have required and received the necessary tempering at about 360 to 390 degrees Fahr. (180 to 200 degrees Cent.) to give it the temper required for service. It is possible to so harden stainless cutlery that the hardening operation will leave it with the correct temper, thus leading to the omission of the tempering operation. Knives, however, which have been hardened in that way are not quite as stain-resisting as when the blades have been properly hardened to begin with, and then had the tempering done subsequently. There is no doubt also that the finish on the blades is worth studying. A blade properly hardened and tempered, which has been ground, i.e., properly "bottomed" and polished to a really good finish, is better than the same blade when indifferently finished. All properly manufactured stainless blades will resist total immersion in 1.20 sp. gr. nitric acid. Hence, this nitric acid test is the one which should be employed for discriminating between stainless and other cutlery. It does not need to be said that stainless blades, if properly manufactured, will resist the acids, etc., encountered in ordinary domestic use.

In this short section I have endeavored to place before you the results of what have been very interesting investigations, and it can be summed up briefly in the following words that:—

- (1) The cutting properties of cutlery are largely determined by the success with which the exact hardness required is obtained.
- (2) This hardness should be periodically determined during manufacture in a quantitative manner on the lines indicated.
- (3) It has been clearly shown that the requisite hardness for perfect cutting properties can be obtained in stainless blades

of all kinds, when properly hardened and tempered.

- (4) The respective characteristics of shear, best cast, and ordinary steel, have been considered, and it has been shown that whereas shear and high carbon cast steel should be hardened from 1400 to 1440 degrees Fahr. (760 to 780 degrees Cent.) and the ordinary steel a little higher, stainless steel should be hardened from temperatures of 1740 to 1830 degrees Fahr. (950 to 1000 degrees Cent.).
- (5) That in the case of stainless steel knives, the hardening should be effective in the first place and that tempering should be done at 360 degrees Fahr. (180 degrees Cent.).

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